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The Journal of Engineering, Science and Computing

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Dear friends and colleagues,

With great pleasure, I am delighted to present you the third issue of the Journal of Engineering, Science, and Computing (JESC) managed and edited by the Islamic University of Madinah, Saudi Arabia.

The mission of the JESC is to disseminate contemporary research work from researchers across the globe in the areas of Engineering, Science, and Computing.

The third issue of the journal attracted a reasonable number of submissions, which brought great pleasure to us. However, our policy stays put and we pledged to present to you a quality research. Therefore, this issue comes with four articles which represent an acceptance rate of around 25%. The editorial board including the Editor-in-Chief and the editorial advisory board would like to thank all of those who contributed to this issue and would like to welcome potential authors to contribute to future issues.

It is a privilege to share with you the third issue of the journal and wish you happy reading.

Mohammad Abdeen, Ph.D., P.Eng.

Editor-in-Chief

The Journal of Engineering, Science and
Computing (JESC)

A handwritten signature in black ink, appearing to read 'M. Abdeen', with a long horizontal flourish extending to the right.

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An Overview of the Implementation Issues of IEC 61850 Based Substation Automation System (SAS)

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Abstract: IEC 61850 standard has gained a tremendous popularity in substation automation after its emergence. Many research papers have been published highlighting the different features and benefits of the IEC 61850. The standard offers interoperability, easy configuration, less cost, and simple architecture. However, in order to avail these features and advantages, there are many challenges during practical implementation which has been discussed in this paper. Previous papers generally discuss about one or two issues, i.e., particularly implementation and security issues, but this paper comprehensively discuss all failures and technical challenges faced by IEC 61850 based substation automation system (SAS). The paper presents a detailed overview of different kinds of issues, i.e., practical implementation issues, structural issues in hierarchical layers, security issues, interoperability and interchangeability issues, communication challenges, planning, reliability, synchronization, availability, training and functional issues, manpower skills, and other issues, etc. The paper discusses issues and challenges which need to be taken into account and should be resolved before the implementation of the standard, i.e., the criticality of IEC61850 based communications in terms of data transfer, reliability, availability and efficiency. In order to get successful implementation, and complete advantage of the standard, it is very necessary to take into account the existing issues and address them before implementing the standard in a utility. The paper also discusses about the future of IEC 61850 standard, and shows that DNP 3 protocol is still very popular among utilities, especially in the North America. The paper also discusses its possible integration with Internet of Things (IoT). Finally, the paper presents a case study of substation with respect to end-to-end delay of time critical Sampled Values (SV) messages in an Ethernet and wireless environment. This study will help the user in understanding the substation primary plants, i.e., current/ voltage transformers (CT's/VT's), circuit breakers, etc., for substation automation, control and protection.

Key words - IEC 61850, SAS, IEDs, Issues, Failures

الخلاصة: اكتسب معيار IEC 61850 شعبية هائلة في أتمتة المحطات الفرعية بعد ظهوره. تم نشر العديد من الأوراق البحثية التي تسلط الضوء على الميزات والفوائد المختلفة لـ IEC 61850. يوفر المعيار إمكانية التشغيل المتبادل، والتكوين السهل، والتكلفة الأقل، والبنية البسيطة. ومع ذلك، من أجل الاستفادة من هذه الخصائص والمميزات، توجد هناك العديد من التحديات أثناء التنفيذ العملي التي تمت مناقشتها في هذه الورقة. تناقش الأوراق السابقة بشكل عام قضية واحدة أو قضيتين، أي على وجه الخصوص قضايا التنفيذ والأمن، ولكن هذه الورقة تناقش بشكل شامل جميع الأعطال والتحديات التقنية التي يواجهها نظام أتمتة المحطات الفرعية المرتكز على IEC 61850 (SAS). تقدم الورقة نظرة عامة مفصلة على أنواع مختلفة من القضايا، أي قضايا التنفيذ العملي، القضايا الهيكلية في الطبقات الهرمية، القضايا الأمنية، التشغيل البيئي وقضايا التبادل، تحديات التواصل، التخطيط، الموثوقية، التزامن، التوافر، التدريب والقضايا الوظيفية، مهارات القوى العاملة، وغيرها من القضايا، وما إلى ذلك. تناقش الورقة القضايا والتحديات التي يجب أخذها بعين الاعتبار ويجب حلها قبل تنفيذ المعيار، أي أهمية الاتصالات القائمة على IEC61850 من حيث نقل البيانات والموثوقية والتوافر والفعالية. من أجل الحصول على التنفيذ الناجح، والاستفادة الكاملة من المعيار، من الضروري جدًا مراعاة المشكلات الحالية ومعالجتها قبل تطبيق المعيار في الأداة المساعدة. تناقش الورقة أيضًا مستقبل IEC 61850 القياسي، وتبين أن بروتوكول DNP 3 لا يزال يحظى بشعبية كبيرة بين المرافق العامة، خاصة في أمريكا الشمالية. تناقش الورقة أيضًا إمكانية تكاملها مع إنترنت الأشياء (IoT). وأخيرًا، تقدم الورقة دراسة حالة لمحطة فرعية فيما يتعلق بالتأخير من طرف إلى طرف لرسائل القيم العينية ذات الوقت الحرج (SV) في بيئة إيثرنت ولاسلكية. ستساعد هذه الدراسة المستخدم في فهم المصانع الأولية للمحطات الفرعية، أي محولات التيار / الضغط (CT's / VT's)، وقواطع الدارة، وما إلى ذلك، لأتمتة والتحكم وحماية المحطات الفرعية.

1. Introduction

Utilities, industries, commercials, and even residential consumers are transforming all aspects of their lives into the digital domain. A substation automation system (SAS) is a digital communication network that facilitates control, protection, and monitoring among various devices. Before the IEC 61850 standard, communication within the substation was established via expensive copper wires with limited proficiency. In order to address multiple SAS issues, IEC61850 standard named as Communication Networks and Systems in Substation was developed in 2003 to ensure interoperability among Intelligent Electronic Devices (IEDs) by the International Electro-technical Commission (IEC) Technical Committee Number 57 Working Group 10 (TC57WG10) and IEEE for Ethernet (IEEE802.3) based communication in electrical substations [1]. IEC 61850 was not designed just as a protocol like previous automation standards but a way of life for a substation, i.e., providing a design guideline for automation systems incorporating best industry practices as well as existing standards. IEC 61850 standard can provide interoperability among devices, reliability for the transfer of data, able to integrate monitoring, protection, and control devices in a network to perform different applications. The standard also defines data models representing all substation devices and functions, and common configuration syntax with a single configuration repository for all devices in the substation automation system using extensible markup language (XML). IEC 61850 clearly exceeds former protocols such as IEC 60870-5-103, DNP3, and other proprietary protocols, in terms of functions and capabilities. Therefore, IEC 61850 can be described as a collection of a management and specification system, a configuration language, a definition of automation services, a vocabulary of automation objects, and a conformity assurance system [2], [3].

In SAS, an IED (a physical device) is the main unit to perform all kinds of functions, i.e., protection, control and monitoring, by generating and handling analog and digital signals. IED is an embedded microcontroller systems that support Ethernet based communication and can perform several automation functions in SAS such as data and le transfer. Similarly, communication protocol, data formatting and the configuration language is defined to provide interoperability among devices. The IED is defined by the network address to start the IEC 61850 standard model. An IED can have one or more logical devices (LD), and a logical device may consist of many core functions called Logical Nodes (LNs) [3]. Hence, an IED is a standard representation of a data concentrator. In this way, a model is provided by the standard which supports devices from different manufactures due to common information approach for each logical node. The standard provides an ability to map available data and services to any available protocol for communication. The standard uses OSI 7 layer stack for communication as shown in Figure 1 [4].

As shown in the figure, standard maps the data to different protocols based on the application.

The type 4 and type 1 messages, i.e., raw data samples and time critical GOOSE, are directly mapped to low level Ethernet layer due to the nature of these real time messages. Sample Value Message (SV message-type 4) is a real time message and it is defined in IEC 61850-5 standard for protection, control, and measurement, etc. The type 6, i.e., time synchronization messages, are broadcasted using UDP/IP stack, while type 2, 3, 5, and 7 messages, i.e., medium speed, low speed, file transfer, and command messages, are mapped to the manufacturing message specification (MMS) using TCP/IP stack. GOOSE messages run over flat layer 2 (i.e., not routable), and non-time critical messages (MMS, web services) run over layer 3 (i.e., routable). For the fast propagation of control signals (i.e., GOOSE message) in wide area networks, the IEC 61850-90-1 (an extension) provides communication among different substation for different applications, i.e., teleportation [4], [5].

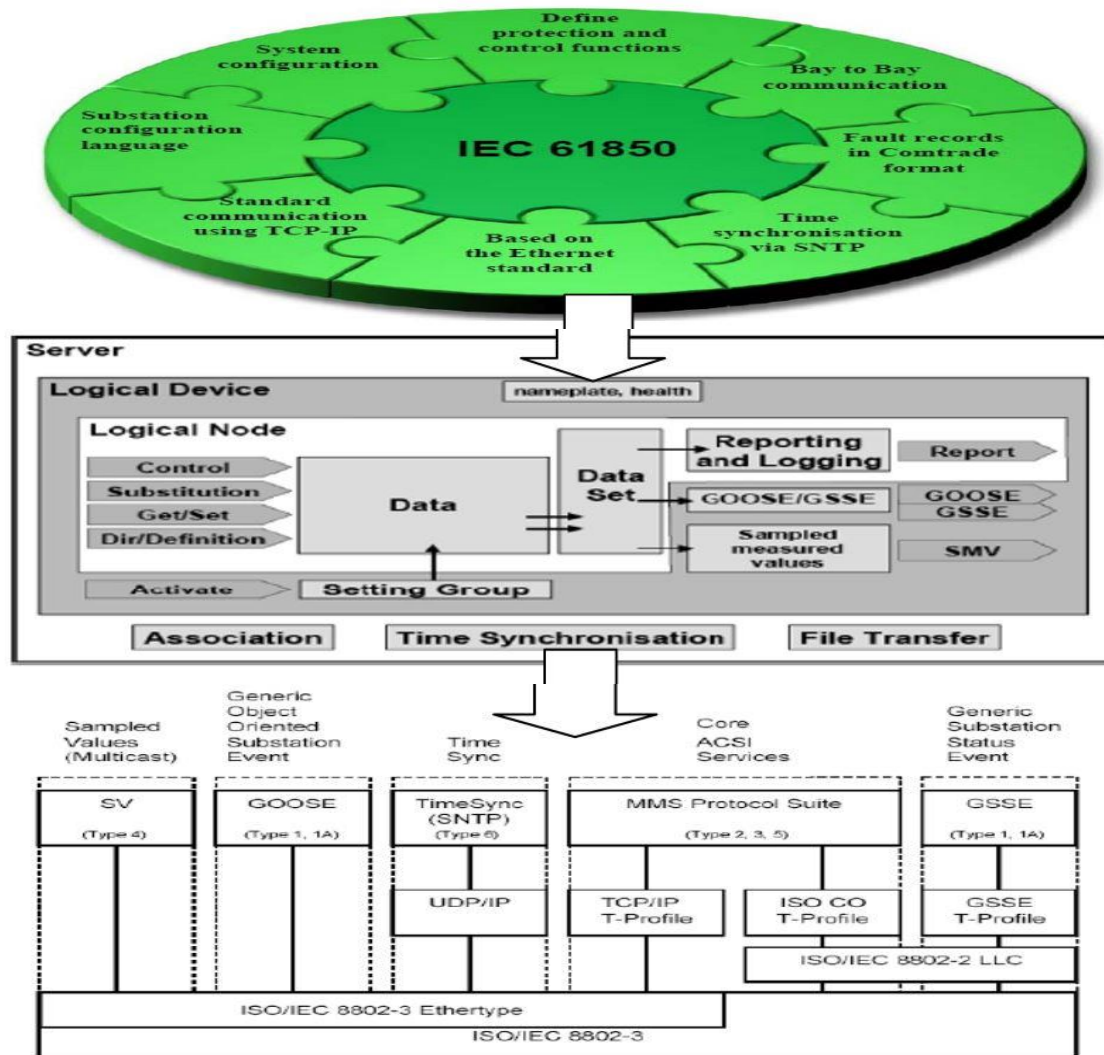


Figure 1. Conceptual model and OSI layer stack of IEC 61850 [27]

IEC 61850 is lengthy, complex and feature rich standard that facilitates the creation of powerful automation systems. The standard has already been deployed in thousands of new substation automation systems worldwide and is gaining popularity in other power system domains. However, the use of new technology and demand has also introduced new set of failures, as compared to conventional control and protection systems, i.e., wire based system. The figure 2 shows the cumulative technical issues per year [15].

There are structural, implementational, operational, data communications, and software failure issues, which were not present in the traditional hard wired systems. Unlike other standards, IEC 61850 was made operational without checking strict security features, and may introduce vulnerabilities for cyber-attacks due to the use of Ethernet based communications. Possible security breaches are password cracking, eavesdropping, replay services, data maliciousness, information interception, etc. Different other possible failures can also be infected to the system with malware by using infected devices [6]. Similarly, many external faults which although are not related to the substation but may cause many failures in the substation. In most of the cases, communication failures are figured out as the root cause of the problems in the substation automation. As Ethernet network is generally the architecture of the IEC 61850 enabled SAS, there are also numerous Ethernet faults and failures. The standard also does not define any particular system architecture and is a perfect tool to obtain interoperability, but there are also many practical limitations in this regard [7].

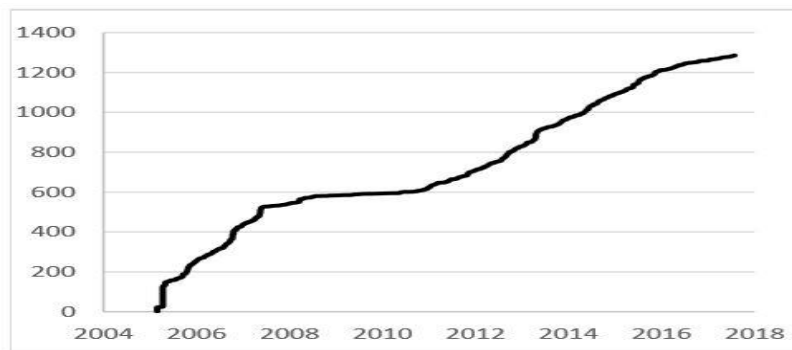


Figure 2: Cumulative technical issues by year [15]

The paper presents a detailed study of the different kinds of structural, implementational, operational, cyber, interoperable, interchangeable, and all other kinds of issues and challenges in IEC 61850 based substation automation system. Previously, different research papers have discussed these issues individually, but they are not discussed in a comprehensive way. The paper will really help researchers working to do their research while keeping in mind about these challenges. The paper will also help utilities to address these issues/challenges while

implementing the standard. Finally, the paper also discusses about the future of the IEC 61850 protocol, and its integration with IoT, while keeping in view with respect to these challenges. The paper makes it clear that if the standard really wants that it should be adopted by the utilities, the issues/challenges must be addressed.

The remainder of the paper is organized as follows: Section 2 describes the failures in hierarchical levels of the substation automation systems (SAS). Section 3, and 4 presents the interoperability and inter-changeability issues, respectively. Section 5 presents cyber-security issues and failures. Section 6 and 7 discusses subscription configuration language and manpower training issues. Section 8 discusses other issues and technical challenges. Section 9 discuss about the future of the IEC 61850 standard. Section 10 discuss about the integration of Internet of things (IoT) with the IEC 61850 standard. Section 11 presents a case study of substation for the end-to-end delay measurement of SV message for wired and wireless architecture. Section 12 presents a discussion, and section 13 presents conclusion. In the following section, the structural issues of the substation automation system have been discussed.

2. Failures in hierarchical levels of Substation Automation Station (SAS)

There are three hierarchical levels in a substation, i.e., station, bay and process level, as shown in the Figure 3 [4]. For communication between these levels, substation uses station and process buses. Following section discusses different issues and challenges related to the substation levels and buses [8].

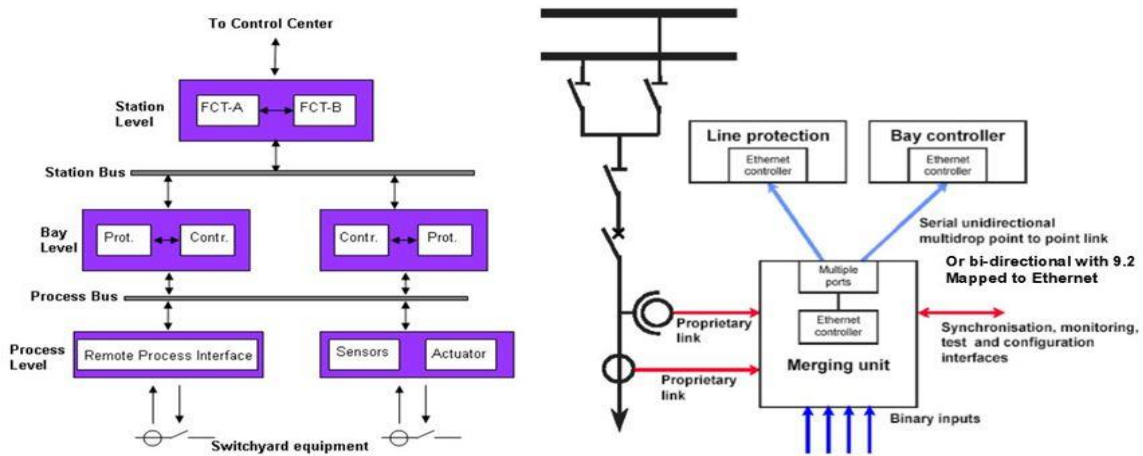


Figure 3. Interface model of a SAS (left) [4], basic Process bus and Sample Measured Value concept (right) [35]

2.1 Failures at the station level: The station level implements those functions which require data from more than one bay. Station level has human machine interface (HMI) computers, communication interfaces, and device configurations. Failures at station level are very

challenging and hard to recognize, which can occur in SCADA (supervisory control and data acquisition) centre and in remote user, and are ultimately transferred to SAS. The server at station level is the most critical part as whole data can be lost if there is a server failure. Therefore, redundant human machine interfaces, and servers should be implemented to avoid failures [4], [9].

2.1.1 Station bus failure: The communication between the station and the bay level is done through station bus. Station bus also provides communication among different bays. There are always communication issues at station bus. Therefore, for time critical protection and control messages, i.e., breaker failure trip, bus differential trip, etc, performance evaluation is needed. Generally devices from a single manufacturer are used in a complete single zone of substation, and protection and control functions are not distributed, so minimum coordination is needed among devices. However, if IEDs are from different manufacturers then it is a big challenge for design engineers to execute the SAS successfully by coordinating all the distributed functions in a single zone of substation. IEC 61850-90-1 and IEC 61850-90-2 discusses about the communication between substations and control centers, respectively [8], [4].

2.2 Failures at the bay level: The IEDs such as bay control units (BCUs), bay protection units (BPUs), phasor measurement units (PMUs), measuring centers (MCs), switch gears, metering gauge, etc., are all placed at the bay level. All of the important tasks such as data collection, protection and controlling the power network, i.e., IEDs receiving data from switches and sending them to servers, and also transferring instructions from HMIs to the interface devices are performed through these IEDs. The bay level has the central position in the hierarchical structure of the SAS; therefore any failure at the bay level has more severe effects on the operation and performance of the substation as compared to other levels. Bay level can have revealed and hidden failures. In revealed failure, if an IED responsible for complete protection and control fails, then whole system may fail. In hidden failures, a failure remain hidden during normal operation until unless some fault occur, i.e., a device may start working when it is not required or may not work when it is required, such as a protective relay which cannot detect or cannot respond when a failure occurs in the system. Self-testing and certain diagnostics should be carried out routinely in order to avoid hidden failures [10], [11].

2.3 Failures at the process level: The power equipment at the lowest level, i.e., switch yard equipment, such as current transformer (CTs), voltage transformers (VTs), protection transformers (PTs), remote I/O, circuit breakers, smart sensors, and actuators, and MUs, are connected to the substation through the process level. The process level is responsible of collecting data in a timely manner from power equipment for proper control. Due to this importance, if any failure occurs then communication among power networks and the SAS is affected. Digital communication is provided by IEC 61850-9 at the process level through the process bus to other station levels reducing the cost and complexity of the traditional hard wires.

Inputs (analog and binary) from switchgear equipment and status information from transducers are gathered using merging units (MUs). The analog values are first converted to digital before sending to the protection and control IEDs at bay level using Ethernet based communication. MU also time stamps each data using time synchronization (GPS clock) in order to estimate accurate phasors for protection and control IEDs. If there is any failure in the data transmission from the merging units to the control and protection IED's, then control (e.g., interlock logic) and protection (e.g., auto-reclosing) functions will be affected. Similarly, sensors and indicators check the power system equipment (transformers and breakers) to acquire, mention, and update to the SAS for any kind of failure. Therefore, if there is any failure in the sensor and indicator, it can also affect the reliability of the substation indirectly [4], [8].

2.3.1 Failure at process bus: Process bus is responsible for the time critical communication i.e., sampled values, and also facilitates communication between IEDs at the bay and the process level, i.e., switchyard equipment. Process bus issues are critical, i.e., handle time critical GOOSE and RAW messages, as all protection and control functions depend on the reliability of the process bus. Figure 3 also shows the basic process bus and sample measure value concept [35]. But on the other hand, utilities still do not have a mature practical experience to work with process bus, and there are still many issues/challenges related to process level communication as described below.

2.3.2 Issues with process bus topologies: There are different ways, called topologies, in which workstations can be connected with each other using Ethernet based communication. The topology really determines the nature and performance of Ethernet local area networks (LANs). The standard did not impose any restriction on the architecture of the process bus. Therefore, different architecture was developed by different manufacturer to achieve greater reliability at process bus but without ensuring interoperability between them. Ethernet topologies offers a speed of 100MBits/s for communication but time critical messages has to be in compliance with the allowable message delivery time as defined in IEC 61850 Part-5. The IEC 61850-5 I.2 studied the performance of the SAS network but without describing how the IEDs are modeled and without taking into account the worst case scenario, process bus, and network topologies. Therefore, the standard does not really specify the parameters for an overall system performance, i.e., performance of the message delivery [12]. Common Ethernet topologies such as bus, ring, star and hybrid used in substation are briefly discussed below with their issues.

a) Bus topology: IEEE 802.3 based carrier sense multiple access with collision detection (CSMA/CD) approach is used in this topology. Bus topology does not use switches, hubs or repeaters, and communicating stations are directly attached to the bus through hardware interface known as a tap. However, the topology is not feasible for large substation process bus as GOOSE and raw data packets time delay in this topology is not in compliance with IEC 61850 standard [4, 9, 12].

b) Ring topology: Ring topology uses point to-point communication links by using repeaters or switches in a closed loop. In ring topology, when one side of the loop is broken, the IEDs are not able to communicate with the IED on the other side of the loop. Although, it is easy to find a fault and rectify it as compared to the bus topology, thus making it most reliable topology. However, this topology is also not suitable for larger SAS as time delay for GOOSE and RAW data messages is the same as bus topology [4], [12], [9].

c) Star topology: In star topology, every station is connected directly to a central switch. The message delivery time for critical application are also in compliance with IEC 61850, but if the central Ethernet switch fails in this topology due to any reason, i.e. technical, environmental and EMI (electro-magnetic interference) conditions, then a major breakdown can happen at process level, and ultimately at whole SAS level [8].

d) Cascaded Star topology: Cascaded Star topology is another topology, in which Ethernet switches are connected in cascaded way, i.e., a switch is connected to the previous and/or next switch in a cascade way. If one of the switch fails, especially at the start of the cascade, system may face considerable delays, or total communication failure. Therefore, complete reliability is still an issue in this topology [4], [12] [8].

e) Star Ring topology: Star Ring topology provides architecture in the form of a closed loop by connecting the last switch with the first one. This topology facilitates some redundancy and reliability in case of failure, and has communicate messages within the allowable message delivery time as defined by the standard, but it is more difficult and expensive to implement this topology with respect to other topologies [4], [12] [9].

2.3.3 Other technical issues with process bus: Other technical issues are described below.

a) Time synchronization issues: Time synchronization defines how IEDs perform the synchronization of their internal clocks with a device using global positioning system (GPS) satellite. The signals sent through the process bus should be synchronized so that the protection and control functions at bay level IEDs can utilize such signals effectively from independent merging units (MUs) of various manufacturers. IEC 61850 standard first defined simple network time protocol (SNTP) to perform synchronization process but this protocol does not provide time synchronization requirements for all SAS applications, i.e., disturbance recorders, synchro phasors and data transferred through the IEC61850-9 process bus, etc. SNTP also provides an accuracy up to 1 ms, which does not meet the requirements for the raw data sampled values [13]. The standard has also proposed many other protocols to address this issue. One of the solutions is to use the inter-range instrumentation group (IRIG-B 9) synchronization which is able to provide the requirements as defined in IEEE 1588 standard and can provide accuracy in the range of 1 s. Another solution is to provide point-to-point communication between IEDs and merging units. Therefore, synchronization is very important along with latency for smooth and reliable

communication between devices inside a SAS or communication with other substations. The data is useless for monitoring, protection, and control if synchronization is lost. Therefore, there must be synchronization while collecting data from the process level [8].

b) Electromagnetic interference (EMI) immunity: Electromagnetic interferences such as switching surges, electro static discharges, etc. are commonly encountered in air insulated substation (AIS). Therefore, all the devices in a SAS must be fulfill the requirements as defined in the EMI immunity standards particularly at the process level. The general EMI immunity procedures used by industry do not follow the air insulated substation (AIS) requirements. The EMI immunity requirements are defined in the IEC 61850-3 with details by referring to IEC 6100 series (IEC 61000-6-5 and IEC 61000-4-x) or IEEE C37.90.2 [8].

c) Variations in IEC61850-9 standard: The standard defines IEC 61850-9-1 and IEC 61850-9-2 for transmitting sampled values on the IEC 8802-3 standard frame. In IEC 61850-9-1, the ASDU (Application Service Data Unit) format is fixed as defined by the IEC 60044- 8 standard. However, IEC 61850-9-2 is more versatile and programmable according to the requirements, as it uses a configurable dataset based on an encoded APDU (Application Protocol Data Unit) according to ASN.1 format. Therefore, the design engineers need to be very careful while designing the SAS [9].

d) Measurement accuracy: The available data at the process bus is analyzed according to the standards before communicating to the bay level. Therefore, the data at switchyards is sampled and then digitalized according to IEC 61850-9 standard, but this process adds quantization error. Similarly, devices such as analog to digital converters and microprocessors further add delay due to the digital signal processing. Also step and frequency response, i.e., dynamic behavior of merging units, need to be analyzed properly [9], [12].

e) Evolution of process bus: The evolution of the high data rate IEC 61850-9-2 process bus has greatly improved the performance of the SAS. However, the utilities still do not have a good understanding that how the process bus will behave under heavy traffic in a network. Therefore, various communications network parameters of the modeled IEDs need to be checked, i.e., various communication link speeds, IEDs microprocessor processing time, packet size, buffers sizes, number and capacity of the queues, etc [3], [11].

f) Interlocking: The integration of IEC 61850 in each IED eliminates the advantage of the protocol contents. Research has shown that interlocking problem occurs in the architecture using Ethernet bus and TCP/IP protocol. The interlocking is due to the delay causing an instruction from a switch to reach to another switch after delay, which is experimentally calculated around 80 msec. The design engineer has to modify TCP/IP protocol for time critical transmission [14].

g) IEC 61850-Part 10 describes conformance testing procedures to check that the IEDs provide the features as described in the subscription configuration language (SCL) file. However, network designer need to verify the other IED performance characteristics which are not

included in part 10 such as synchronization, time- stamp accuracy, control reaction time, operational and reliability criteria. The good engineering design is to select IEDs that will continue to function without delay even if network failed or it is under attack [15].

h) Research has also shown that the packet size is also one of the main factors which cause delay. Therefore, small packet size should be used, and should also avoid sending a variety of data streams at the same time in order to meet the real requirements in the substation [16].

i) Factors like distance and location of the MU and IEDs, the communication capabilities (single port, multiple ports) of the units, the availability of the network, bandwidth, and the communication topology (point-to-point, star, or ring) can make the selection of the process bus architecture quite complex.

j) IEC 61850 is based on the inter-relay communication capabilities. Therefore, redundancy of key components is very important for the overall reliability of the system, i.e., particularly dealing with protection issues.

k) There can be a delay and packet losses on process bus architecture based on IEC 61850-9-2, causing significant effect on the reliability of the protection system for whole network. Research has also shown that by increasing the frequency of the SV messages causes more packet drops [17].

l) During up gradation and migration to IEC 61850, a secondary system should be there to support both conventional and nonconventional instrument transformers [12].

m) A larger bandwidth is required as process bus needs to continuously transfer sampled values from the primary process with a quasi-real time response.

n) Electronic interfaces must be used with circuit breakers and digital switching must be used to convert switch positions, and commands.

o) There are many other issues which a designer has to take into account while using Ethernet LAN such as status of automation and protection when LAN fails, IED performance and its communication if there is a heavy traffic, hacking, denial of service, performance of the network during overload, effects of the newly connected IED on network, performance of the functionality issues of the IED as single CPU might suspend protection while servicing other network request [16], [13].

All of the above mentioned issues clearly show that there are lots of issues with process bus, i.e., ranging from its topology to technical challenges. Hence, the architecture of the process bus in the utility needs further validation due to the lack of this confidence. Following section will discuss the issues with respect to interoperability, i.e., how devices from different manufacturers will communicate with each other.

3. Interoperability

It is a big challenge to provide interoperability among devices from different manufacturers. One

of the main ideas for the formation of the IEC 61850 was to provide enhanced interoperability among IEDs from different manufacturers to perform different functions, i.e., protection, interlocking, and automation [18]. However, design and configuration is still needed for the two IEDs to interoperate with each other even with the same message type [8]. This is due to the reason that different protocols are used to perform communications between IEDs belonging to different manufacturers, which are not compatible with IEC 61850. Therefore, additional protocol inverters are required which are costly and increase failure chances. Although, the standard tells how the data will be communicated and analyzed between devices from multiple vendors but the standard does not tell which data will be available. Similarly, whenever there is upgrades in the hardware or firmware, compatibility issues occur, and even if all the configurations of two different devices match, there is still a possibility that these two may not communicate properly [13], [19], and [20]. Therefore, there can be many issues with respect to interoperability, as discussed below.

3.1 File transfer: File transfer is an issue, as IEC 61850 supports both FTP (File transfer protocol) and MMS (multimedia messaging service) file transfer but does not standardize the contents. Therefore, consistency or interoperability of these files among different vendors is still an issue, i.e., a product from one vendor may not be interoperable with other vendor. There are also other issues found between vendor files such as incorrect initialized values, unsupported XML namespace issues, support of integer 128 issues (inability to map/support such a value in the implementations memory/application), issues when a vendor attempts to import an SCD (substation configuration description) file exported by another vendor. Therefore, it becomes very challenging to confirm the performance of the substation, if IEDs belong to different manufacturers as even if IEDs pass the conformance test, there is no guarantee for interoperability and satisfaction of end users requirements. Therefore, utilities and end users must include the interoperability test for the IED acceptance process due to the existing ambiguities, i.e., different manufacturers have different interpretation of the IEC 61850 standard. These issues not only vary the interoperation of the standard from one vendor to another, but further enhance the complexity of interoperability tasks within the SAS [8], [7].

3.2 Version upgrade issues: IEC 61850 provides free configuration by separating functions of each section in the substation. Hence, the reliability of the operation in any section depends on the configuration of all devices from multiple vendors in that section. Therefore, if a version update is done for the hardware or software of a single device, then it may not interoperate with other devices belonging to other vendors leading to a need for updating of the hardware or the software of all the devices installed in the same zone causing more time, money, failures, and complexity.

3.3 Challenges for the system configuration: The IEC 61850 standard defines IEDs model, communication services and various common files but it does not specify the IED or the system configuration tool. The protection and integration engineer face severe challenges while

configuring individual IEDs or even the whole system due to various manufacturers IEDs and system configuration tools. Therefore, the configuration task is the most costly and time consuming process based on the available SAS configuration tools.

3.4 Automatically map configuration Issue: For a complete communication among client and server, a one to one correspondence of necessary protocol attributes is not available, therefore a manual configuration is performed as automatic configuration is not available. The system integration performed in this way is very time consuming. Similarly, some other instructions get benefit from the IEC 61850 object oriented data structures, but many data structures are not available in other protocol standards. Therefore, new data aspects are generated along with the requirement of changing current data attributes from one format to another.

3.5 Other issues regarding interoperability: Single vendor IEC 61850 interoperability is fine, but there are always challenges and problems for multivendor implementation. Utility workers need to be trained to use specific vendor tools to configure the system in a multi-vendor environment. In north American utility, there is an interoperability challenging list such as point naming differences (some vendors use generic names and others use specific contextual names), configuration parameter differences disallowing one vendors IED to subscribe to GOOSE message from the other vendors IED, challenges with respect to SCD configuration files and how to upload to devices as there is no area within the native IEC 61850 files and needed to use the private data sets to support the different settings file and IEC 61850 file. Moreover, there are different limits for number of publishing messages and number of subscribing messages for each vendor IED, as some vendor IEDs do not support priority tagging for GOOSE messages, and some do not support VLAN identifiers for network segregation. Similarly, automatic configuration using vendor SCD/ICD (IED Capability Description)/CID (Configured IED Description) files is impossible [19].

The reality of the IEC 61850 interoperability is that vendor wants coexistence and utility want interchangeability. The MMS and GOOSE messages have high maturity, while semantic model has medium maturity, and engineering tools have low maturity. Many utilities assume that products of different vendors have implemented all parts of the standard in a completely interoperable way but this is actually not right due to the reason that IEC 61850 is a large standard with multiple options from which the vendor can choose, and the marketing departments of each vendor make individual decisions concerning the features set that their customers will only use. Also, some parts of the standard can be interpreted differently by different vendors. Therefore, in order to create a successful network, a network designer has to check that the IED is able to work with the required data, protocols, and characteristics of the IED coordinate well with the other devices in the network [14]. In the following section, challenges/issues with respect to interchangeability are presented.

4. Interchangeability Issues

Interchangeability is another challenge which needs to be addressed to provide a complete flexibility to replace an IED with another IED belonging to different vendor in the same network with minimal changes. Enhancing the capability of the substation is a major challenge, i.e., augmentation, as IEDs belong to different vendors and integrating them with existing hardware (HMIs, IEDs, switches, etc) is both an economical and technical challenge. The utilities want interchangeability at the abstract communications service interface (ACSI) level so that they can select IEDs whichever they want from different vendors, as the IEC 61850 standard never ensured interchangeability of IEDs. The standard also does not define which logical nodes or contents will be supported making interchangeability more complex. Integration efforts can be minimized using standardized names and attributes in LN, but reconfiguration is still needed when devices are changed with different logical nodes, GSE characteristics, database, and interfaces. The integration can be reused if the characteristics are same, but device interchangeability is limited due to reason that logical device name is not configurable. Although, IEC 61850 is not just a protocol; it is a way of life, but utilities should avoid big changes as it may lead to strong disagreements between users, implementers, consultants, and manufacturers [17].

4.1 Observations regarding different vendor's equipment implementation: IEC 61850 needs to be continuously assessed for reliability. This is due to the reason that understanding and implementation of standard varies between from one vendor to another. Therefore, devices may behave differently even working under same condition. The research has also shown that the implementation of the GOOSE on commercial IEDs and on the open source libiec61850 library shows different results even under the same conditions, which sometimes provides an opportunity of cyber-attack on the devices under the study [7].

Cyber security is another big issue for reliable and secure operations as described in the following section.

5. Cyber security

Cyber security is always a big threat, i.e., pirate intrusion attacks leading to a compromise of data security, consistency and integrity. In cyber-attacks, PCs are infected, files are encrypted, and ransomed is asked. Also, NISTIR 7628 (a guideline for smart grid cyber security) has specified IEC 61850 as an insecure protocol, i.e., substation LANs are vulnerable if there is no implementation of firewalls, intrusion prevention system (IPS), intrusion detection system (IDS), data gateways or demilitarized zone (DMZs). Cyber-attacks on substation automation systems are real and increasing, leading to large financial losses. There was a cyber-attack in Ukraine in 2015 and 2016, where adversaries gained full control to SCADA and control room functions, and interrupted power to several customers in both attacks, and implemented a telephone denial of

service (DoS), uninterruptable power supply (UPS) shutdown and kill disk phenomenon [21]. IEC 61850 does not define any mechanism against cyber attacks, and it is up to the manufacturers to fulfill the requirements as specified in IEC 62351. Ethernet based communication has made SAS more vulnerable to cyber-attacks. Automation system has been opened to external world and can be misused for cyber-attacks. Automation industry should follow regulatory directives or industry best practices to avoid any liability. The automation industry will not be in position to offer required customer needs, high level of security for all products and solutions, fast response and reliable partner in case of a cyber-attacks. The vulnerabilities can be on the device level and on the network level. On the device level, when firmware of the subscribing devices are configured, i.e., GOOSE message communication, it must be properly tested and verified that it must follow the requirements as defined by the IEC 61850-8-1 and IEC 62351-6 standards. The subscribing devices must not process any messages which has repeated or old status numbers. The libIEC61850 has a function, i.e., IsValid(), to make sure that no duplicated or old numbers messages are processed, but commercial IEDs do not perform this verification and process fictitious messages. Similarly, any message must not be published and/or processed, until the time stamp with current status number is verified. On the network level, MAC (Media access control) address spoofing is a big issue. MAC filters should be used at all switches in a network in order to stop publishing fictitious GOOSE messages using a spoofed MAC address. However, this thing has not been addressed in both IEC 61850 and IEC 62351 standards [7], [1], [22].

Cyber security is very challenging in the power communication system as IEC 61850 is vulnerable to different attacks, i.e., denial of service, password cracking/swamping, eaves-dropping, interceptions (Man-In-The-Middle) and viruses, etc [23]. These attacks cause delays in message deliveries, and also loss of data and data security becomes more critical while communicating with components in the network whether inside or outside. The standard 61850-3 refers security details in section 304 of the IEC 60870-4. The WT15 of TC57 provides some measures against cyber-attacks, i.e., firewalls, encryption, and authentication, which can provide security up to some level. However, any process to improve the safety of the network will also increase the processing time sacrificing the network performance [1], [21]. Few examples of cyber-attacks are described below.

5.1 Denial of service attacks: During denial of service, large numbers of fake requests are sending from many devices in the network to a particular device in the same network, which ultimately can consume the resources of the network. A denial of service attack prevents an authorized user or machine from accessing the services due to insufficient bound checking, i.e., by disrupting or exploiting the services of an IED. In disruption, a malicious message is sent by the attacker to the attacked IED, which aimlessly writes extra data and causes a buffer overflow and/or an unauthorized data modification. In exploitation, multiple sessions are opened by an attacker on either the file transfer protocol (FTP) or telnet services and then do not use

them and ultimately interrupt the services of the IED [9].

5.2 GOOSE poisoning: GOOSE poisoning is another way of denial of service attack having three different kinds: high status number, high rate flooding, and semantic attacks. The sender and receiver of the GOOSE messages are described as the publisher and the receiver, respectively. Every GOOSE message has a status and sequence number field (stNum, sqNum). In high status number attacks, the attacker tries that the receiver should accept those GOOSE messages which have a higher stNum and consider the actual GOOSE messages as outdated, i.e., creating a possibility of accepting the messages only from the attacker. These kinds of attacks are really dangerous and can damage devices and even cause loss of human life. This kind of attack model is represented in Figure 4 (left). Similarly, an attacker might block legitimate messages and inject messages with altered content leading to GOOSE message manipulation.

Denial of service could also happen due to the high rate flooding attack. The high rate flooding can happen due to the congestion of the channel and utilizing the available computational means of the network, and ultimately delaying messages above the critical delay, i.e., 3-4 ms. Flooding attacks are done at the network or application layer, and can be classified as broadcast flooding or unsolicited flooding, or flooding to a third node [1], [12].

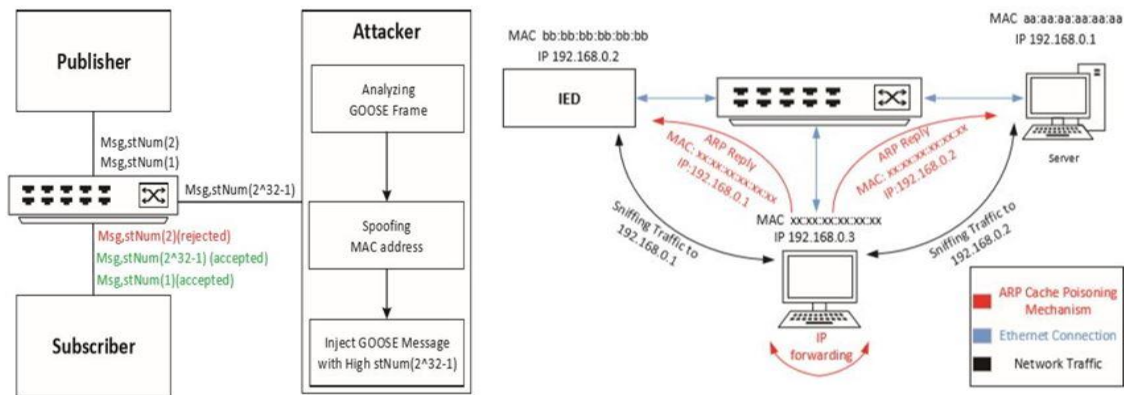


Figure 4: GOOSE Poisoning Attack (left), ARP Cache Poisoning mechanism (right) [1]

5.3 Password cracking attacks: These attacks happen when attacker gets the unapproved control to a system. Brute force attack or dictionary attacks are the two ways to figure out an authorized user password. In brute force attack, a time consuming process is done to find out the actual password by trying all probable combinations of a password, until an actual one is found. Dictionary attacks guess the password by properly constructing words that would be found in a dictionary, and take less time to crack the system [1].

5.4 Packet sniffing attacks (eavesdropping): In these attacks, an attacker attempts to steal the packets which are transmitted on the network by reading them. The services like FTP, HTTP, and

Telnet do not protect their messages and are highly vulnerable to attackers. Packet sniffing attacks also provides an opportunity to attackers to do man-in-the-middle attacks. The attacker may also do eavesdropping by performing an address resolution protocol (ARP) cache poisoning as shown in figure 4 (right), where ARP protocol converts IP addresses into MAC addresses. Therefore, if the attack is successful an accurate IP address is attached with a fake MAC address, and then all the packets are transferred to the attacker instead of actual IP address. This is also done by filling the content addressable memory (CAM) table with fake entries by flooding it. When the CAM table becomes full, packets sent to a MAC address which is not present in the CAM table is published to the whole network providing an opportunity to the attacker to access them. Similarly, in switch port stealing (another way of eavesdropping) the attacker attacks the switch by sending fake frames to change the CAM table in order to connect the MAC address of the attacker to the interface. In this way, all the incoming packets are delivered to the attacker instead of the actual receiver [1].

5.5 Security protocol IEC 62351: IEC 62351 does not provide a complete solution to avoid cyber-attacks, as it can only avoid eavesdropping/man-in-the-middle attacks, switched network packet sniffing through TLS (transport layer security) encryption, message authentication, and describing role based access, respectively. IEC 62351 does not provide protection against denial of service, GOOSE, and SV based attacks, as IEC 62351-6 digital signatures and encryption demand more than the available 4 ms delivery constraint by the IEC 61850-9-2 standard for the generation and verification [13].

5.6 Interception: During interception, attacker gets access to the data travelling in the network by interceptions, i.e., pretending a device which belongs to the network. In this way, the interceptor is able to access the data exchanged inside the network, and can change data values.

5.7 Viruses: Viruses are malicious software that can damage computer systems. If a virus gets inside a computer, it has the capacity of creating copies of them and reaches to other systems in the network.

5.8 Other issues: Research also shows that the GOOSE messages status numbers are not implemented on the devices as specified by the IEC 62351, creating a possibility of an attack on the power systems. Similarly, using old time stamps for processing messages also creates a vulnerability of attacks. Moreover, broadcast nature of the GOOSE messages also creates an environment of the sniffing and rebroadcasting them, specifically when the attacker is sitting in the same LAN. At network level, as long as the GOOSE message has an authentic APPID (application identifier) field, it is processed whether coming from an approved device or a malicious one. The IEC 61850 and 62351 do not define any rules for the authentication of MAC addresses, the utilities have to create appropriate defense mechanisms to address this challenge [24], [2].

The following section describes the issues related to subscription configuration language.

6. Subscription Configuration Language (SCL) issues

In order to standardize the method of communication within IEDs, i.e., configuration between IEC 61850 client or server or the integration of logical nodes and generic substation event (GSE) messages, substation configuration language (SCL) files were created. Substation configuration language is based on extensible markup language (XML) as per IEC 61850-1 standard providing a common object and configuration description. The clause 9 of the standard IEC 61850-6 specifies that SCL XML has five sections [18]. Initially, there was a misconception that by using a self-description method SCL files will be acquired directly from the IEDs. However, it was quickly realized that it is not like this and the system designers has to configure the IEDs by themselves during the settings implementation phase., as most of the configuration tasks are not addressed, and even the configuration to perform primary tasks is not available by using the SCL files. Also, SCL files do not handle automatic, total application configuration and GSE configuration of the IEDs from different manufacturers. Moreover, the standard does not handle interlocking, distributed protection and specialized automation. Therefore, in order to configure each IED, software of the particular IED is required from original vendor for the creation and installation of the logics as no standardization is available [25]. Therefore, tests are required to make sure that devices from different vendors can understand the information files from each other. In some case, even when the configuration files can be easily read and understood, integration with different vendors is still difficult and complex. This happens due to the reason that many parameters of the configuration, engineering and device interconnection are different among vendors, i.e., fixed data sets versus dynamic data sets, etc. [5]. Similarly, the informal specification needs to be converted into technical documentation to do the integration in SCL, and system designer needs to be very careful during this implementation process. The compliance checking has also to be done in detail which is given in part 10 of the standard, and data sheets are provided by the suppliers describing the SCL description and its capabilities with the instructions to save the documents in the subscription configuration description (SCD) file. In fact, the SCL is one of the most difficult parts to understand, as it includes the majority of the design artifacts from the automation project [21], [26]. The following section describes the manpower training issues.

7. Manpower training issues

Other than implementation, interoperability, interchange-ability, synchronization, and cyber security, etc, there are also many other issues for the implementation of IEC 61850 standard. Study shows that the implementation of the standard by utilities is a complex process which needs proper skills, competency, required training, ability to handle challenges while applying new standards, and the deployment strategies for substation automation within existing functional organizational structures, vision, and strategy as shown in figure 5 [27]. Eskom, a

South African utility, who decided to adopt the IEC 61850 standard into its substation, found that the major hurdles for the implementation of IEC 61850 standards were skills, organizational culture, and training and competency levels. As organizational culture is very critical element, hence the implementation of IEC 61850 must be properly studied. Utilities need to train their workers with the latest technologies. The requirements for the core technical skills and competency may change the organizational culture, training and competency levels, and new engineering processes, specifications and tools may be required. Generally, following skills or understanding is required before implementing the IEC 61850 standard such as understanding of protection and control functions, SCL, communication networks (TCP/IP, Ethernet, switches, routers) and time synchronization via SNTP, network data analysis, communications services, mapping of information models, MMS etc. A team of experts from communication, protection, maintenance, and substations should train workers, focusing on the details of the standard. Similarly, devices should be chosen based upon functionality, 61850 requirements, conformance tests, and redundancy [15], [27].



Figure 5: Framework for competencies [27]

The next section presents many other technical challenges, and issues of IEC61850 standard.

8. Other miscellaneous technical issues

There are also many other issues/technical challenges as described below.

8.1 Ethernet network failure: Substation automation system uses Ethernet network which consists of connectors, routers and switches, etc., for the data communications on three different levels of the SAS. Due to the use of connectors and other switching devices, many physical faults and failures like defective network interface card (NIC), faulty cables, unnecessary termination, or extra length cable can occur in the network structure. The failure of NICs, routers, and switches at the physical layer are one of the major issues that can halt data communication in a SAS. Similarly, if a node becomes disconnected or unplugged due to cable dysconnectivity in Ethernet network, and if no redundant path is provided using either, i.e., rapid spanning tree

protocol (RSTP), high availability seamless redundancy (HSR) protocol and/or parallel redundancy protocol (PRP), then a segment of the network or whole system in SAS might get interruption, and ultimately will result a total communication failure. Due to the Ethernet network, jabbering is another inherent issue in these networks, in which a packet has to retransmit when other devices don't understand, resulting in an increased traffic and consequently network halt or failure. Also, if a network is not properly designed, then collisions may occur which generates runts (smaller packets as compared to required minimum packet size) and giants (larger packets as compared to required maximum packet size). Although, routers and switches can be used to reduce the length of the cable and collisions but these devices have their own failure rates, and other faulty issues, ultimately deteriorating the whole system reliability. The IEEE also does not allow any 100BASE-TX segment more than 80 meters in a network [8].

8.2 Commissioning issues: IEDs require lot more configuration, i.e., a complex and time consuming process as compared to a traditional electro-mechanical relays and will not work properly if setting is not done accurately. While commissioning, different kinds of functions in an IED requires validation so that all diagrams, controls, inputs/outputs, indications etc, are working as required. Also testing, which is an important part of commissioning and routine maintenance verifies the correct operation of the IEDs but requirements are altogether different than an electromechanical relays and hard-wired circuits as described in 61850-10. Testing becomes more critical and creates uncertainty in the integrated IEC 61850 based SAS when some part of the system needs to be tested without effecting the working and efficiency of the whole substation. Therefore, any inaccurate SAS engineering and design issues will ultimately lead to operational failure, and may cause the system to allow or stop the requested instructions [4].

8.3 Important things while commissioning: While commissioning, few of these things must be properly understood, i.e., how much important is testing and capturing the GOOSE during commissioning? How to monitor GOOSE message after the system is in service, and how to find the absent GOOSE messages? Is there a limitation to the number of subscribers for one GOOSE? How to visualize the source and destinations of GOOSE? How to replace the new relay of different model or different manufacturer, as testing is required to make sure that all new GOOSE and all IEDs related to this new IED is working properly. The maximum number of IEDs that can be put in one loop on Ethernet switch should be properly analyzed, and communication port of IED should be checked. Similarly, we should take proper measures to manage the files, otherwise it will be lost. Dataset sequence must be followed, as by changing the sequence of the members in the dataset of sending IED during the commissioning process, there is a possibility that corresponding function in the receiving IED will be affected. Commissioning details should be carefully planned with communication and post-communication maintenance tasks. Similarly, how to test an in-service automation system, as legacy air-gap method will not work with IEC 61850 standard [15], [26].

8.4 Data integrity issues: The connection of two points is not always sufficient to have a secure communication, as various other factors also affect proper communication. Logical problems are generally more complex and difficult to find and solve than the network structured problems [4]. Therefore, data integrity is an important issue for a consistent and reliable communication in the standard. IEC 61850-3 standard has referred IEC 60870-4 (section 3.5) for the details of the reliability of the data delivery by the substation. For consistent and reliable communication, error corrections can be performed but this process requires time synchronization further adding the reliability and consistency concerns. Similarly, software failure is another kind of failure which was not present in the traditional hardwired system, i.e., code faults due to the dedicated software of each IED to implement functions. A good level of understanding is required for effectively utilizing different features in an IED due to the complicated software design. Variables, arguments, codes, operands, and subroutines, etc., are the various variables factors which can cause failures in an IED. Moreover, use of latches and time-delays to perform protection and control functions further enhances the probability of software failure. Similarly, if a database fails, it means the massive failure for the operation of running systems. Therefore, any unauthorized access must be avoided to a database [4].

8.5 Latency issues: Latency is another critical issue for the proper operation of Ethernet based network. High speed time critical messages, i.e., GOOSE and SV, require 3-4 ms to reach the destination, as defined by the standard. Each task has some latency but some tasks like system protection must operate in quick and steady way. Two different kinds of latency can exist in a network, i.e., constant and variable. Constant latency is predictable and calculate able as it is an inbuilt delays in devices and connections and also due to the structure of the network and available bandwidth. Variable latency depends that how much is the traffic and current load on the network. The variable latency increases and throughput decreases when there are simultaneous communications or failures inside the network. The issue of latency goes critical if an intermediary device or connector fails, forcing data to travel an alternate and non-optimal path, i.e., increasing the hop count. Similarly sometimes, some intermediary nodes need to handle more traffic in order to cover up the faulty nodes in the network, ultimately increasing traffic delays [13].

8.6 External failures: There can be many external failures, which can impact or halt the operation of a SAS. Most important of them is the loss of power in an IED, as compared to the electromechanical relays. Even if power goes off for a very short moment of time, whole system is reset creating a possibility of failure. Similarly, the loss of power has same effect on network switches, routers and other devices, i.e., a disconnection of all IEDs. A redundant power source is required to avoid such situation [5].

8.7 Environmental issues: The devices at the process levels are exposed to the atmospheric conditions. The environmental requirements, i.e., temperature, humidity, pressure, pollution, and

corrosion are defined in standards IEC 61850-3, IEC 60870-2 and IEC 60694. It is very important that devices at the process level must fulfill these requirements. A build up of the stain and dust on the devices can decrease the efficiency of the cooling system bringing different components in the devices to heat up and also initiate fire in extreme weather conditions. Overheating can also cause temperature sensitive elements to damage if there is no air conditioning, especially in large facilities. Similarly, communications devices, wirings, and connectors decrease in efficiency with time and network performance is gradually reduced [8].

8.8 Planning issues: IEC 61850 standard is very comprehensive in the desired outcome for an interoperable system but the proper application of IEC 61850 standard requires a careful plan. The implementation of IEC 61850 technology requires a large degree of risk management, as learning curve for the standard can be very steep, and training costs are generally underestimated, stopping many substation industry to make transition from old system to a new standard [17]. Similarly, functions in a single section can be distributed to many devices as defined by the standard. However, random or improper allocation of distributed functions may create more traffic in the network increasing message delivery time of the critical messages. Similarly, with the increase in the power demand substations need to be expanded but standard does not specify any specific architecture, and this issue should also be taken care during planning, i.e., adding more devices should not increase and existing Ethernet LANs should be scalable [28] Therefore, for a successful substation commission and execution a complete flow chart should be prepared.

8.9 SAS structural issues: IEC61850 standard guarantee that even a single zone can have devices from different vendors as contrast to the current situation. This means that different devices and Ethernet switches will be from different manufacturers, which may cause problems of communication between each other especially when the devices have to comply with the IEC 61850 standard. Therefore, building such a structure from different vendors also brings risk and complexity to the SAS architecture [18].

8.10 Overall system reliability issues: There is no demand for redundancy in the standard even for critical applications. However, reliability and consistency requirements are defined in the IEC 61850-3, that substation must keep on working all the time and there must not be a single thing which can stop its working, i.e., no loss of any undetected function if any component fails. The details of the reliability requirements for SAS are further defined in the IEC 60870-4 Section-3.1 [8].

8.11 IEC 61850 SAS functions reliability issues: The IEC 61850-1 defines the concept of a distributed function, i.e., splitting the functions into many parts and executing within various IEDs. The reliability of the IEDs, protection, control and automation functions are responsible for the reliability of the system. Therefore, there should no single point where there can be a possibility of failure of a function to cause the whole system to stop working. Previous research papers generally focus on whole system reliability using various calculation methods, and do not

focus on the reliability of IEC 61850 functions. Therefore, understanding the reliability and probability of the failure for any function is very important for a successful operation of a substation [29].

8.12 Accessibility issues: SAS accessibility is also one of the important functional requirements for implementing the SAS according to the standard, and specific accessibility requirements are defined in IEC 61870-4 Section-3.3. Therefore, there may be a need for the back-up to maintain the current level of accessibility for critical applications, as few communication devices may have less availability in the EMI environments, and need to be added in today's architecture [29].

8.13 Sustainability issues: The sustainability issues deals with the inner workings of the IEDs and are defined in the IEC 60870-4 and referred by the IEC 61850-3. In order to fulfill the requirements of the maintainability, there will be more burdens on the manufacturers.

8.14 Cost and complexity issues: IEC 61850 based substations cannot be successful if it is expensive to run its operational functions. It is the cost equation, which finally decides what can be employed in the field rather than what is manufactured, based on what is technically possible. Cost includes engineering design, construction and material cost, availability, and maintaining extra electronic equipment. Similarly, most of the substations are not new but either expanded or upgraded. Migration to IEC 61850 requires large investment making the process long, continuous, and complex. Therefore, there should be a seamless migration during the implementation of IEC61850 standard within specified time limits [18].

8.15 Logical node issues: IEC 61850 does not standardize which logical node should exist in an IED and most of the logical node content in the standard's documentation is optional, or may not be available or mapped. Even if some or all of the logical nodes are supported by the different IEDs, IEC61850 does not standardize the contents of the data. Therefore, there can be different collections of LNs in each IED, and the same LN in different IEDs can have different data. The standard only specifies that the logical nodes are supported and data is identified in SCL by an IED. However, this thing may create many problems and network designers have to get the SCLs and/or other parameters well in advance for selecting IEDs. IED is capable of creating and providing lot of information but the information mapped to the LNs is only available to the network designer. Therefore, in the standard, there will be different data availability between different IEDs [13].

8.16 A big standard: The standard is very big, and there are more than 40 total parts in IEC 61850, 14 of them are in core edition with a variation from easy to difficult understanding for each part. The easy parts document the common understanding of users while the more difficult parts involve issues where there is no right answer for every application. The standard is still evolving as mentioning different technical issues shown at (TISSUEs) even after 15 years [30].

8.17 Miscellaneous issues: Research has shown that there are many other issues because of IED

limitations and was unsolvable and forced the network designer to change the databases and naming conventions for the devices. One of the limitations is the eight character limit of the device name, so a redefinition of the naming database, and correspondingly a reconfiguration of the whole databases are required. Similarly, generic nodes are used as there is no mapping flexibility, i.e., mapping any IED digital value to a data object in a logical node. There are also issues while configuring HMIs and SCADA gateways during functional testing, i.e., control block names cannot be configured for all IEDs, and consequently writing to the report control block name is not possible. Some IEDs also do not have the ability to report something back to the HMI. Similarly, mapping is also an issue when double point indication is done with DNP3 and Conitel 2020 for breakers and sectionalizers. Moreover, servers are not able to handle the large number of IEDs, which can be accommodated in a project. Also windows version compatibility with new version of IEDs is another issue [15], [31]. Similarly, research has shown that issues are there while testing GOOSE messages for interlocks. Control block reference (CBR) cannot be more than 32 characters for some IEDs and many vendors cannot use selected CBR as limit exceeded several times due to the used naming convention. Similarly, some vendors are not able to subscribe the GOOSE messages from different devices by (import SCL files) from other vendors without respecting all the configuration parameters [31]. The available configuration and certification only provide some necessary task for a successful commissioning. It is the duty of the network designer to be sure that all the required data is supported by the IED and it is aligned well with other devices in the network.

Previous sections have presented many possible issues, challenges, and failures, which a utility can face while implementing IEC 61850 standard. There are many concerns such as standard is too big, challenging, difficult to understand everything, require rigorous amount of experience, and a huge possibility that system will fail or will give lot of troubles while implementing. Therefore, all of the above mentioned challenges and issues make it more difficult for a utility to adopt this standard. Therefore, if standard really wants that it should be adopted by utilities, it must have to take into account all possible measures to address these challenges and issues. The next section discusses about the future of the IEC 61850 standard.

9. Future of the IEC 61850 standard

There are many protocols which are used inside the SAS, i.e., distributed network protocol (DNP3- IEEE Standard 1815), IEC 870-5-101, IEC 60870-5-104 and Modbus, etc. The IEC 61850 has major advantages over these legacy protocols used in the substations on the data side, but it also has lot of issues and overheads as mentioned above. DNP3 is one of the leading protocols in North America utility. DNP3 evolved from traditional SCADA requirements for remotely monitoring and controlling assets in a reliable manner over a wide area using low bandwidth and potentially unreliable communication systems. It also provides a relatively

simple data values and control commands with a high degree of integrity and resilient methods for recovery from communication system failures. DNP3 has also seen wide adoption outside of the electric power systems, particularly within water and wastewater utilities. An IED in DNP 3 command requires only two attributes to be set to work on it as compared to six or more attributes required by IEC 61850 protocol. For commissioning of the IEC 61850 substation automation system into a North American utility, it has to interconnect it to a SCADA system which uses DNP3. A new standard, IEEE 1815.1, provides guidance on mapping data and functionality between IEC 61850 and DNP3. However, this mapping process automatically associates IEC 61850 semantics with each DNP3 data object allowing the semantic information known to the DNP3 outstation and masters, although never transmitted over the channel at run time. This improves the efficiency of DNP3 by getting rich object model information available from IEC 61850 [22], [32].

Newton-Evans Research Company conducted a survey in 2016 in North American protective relay marketplace. The participants in the survey were 79 electric utilities that include 16 investor-owned, 28 public power, 26 cooperatives, 4 electric power consulting groups, and 5 Canadian electric utilities. The question was asked whether your utility control system uses IEC 61850 protocol for substation automation or SCADA system. The response of the utilities were very surprising as about 80 percent of the respondents said that they have no use or plans for IEC 61850 in any area, and 89 percent said they don't use or plan to use IEC 61850 for SCADA. These results show that IEC 61850 is more complex as compared to other protocols and industry will take time to fully adopt it. Therefore, the standard will not overpass DNP3 in North American market in the near future. Survey also shows that especially LAN based DNP3 is still the most popular protocol in the industry in their future planning [33].

Although, the IEC 61850 standard offers many advantages due to its open nature, i.e., an availability of a wide range to operate, but it also increases the complexity of the IEC 61850 implementation task. The biggest disadvantages of IEC 61850 based SAS is that this standard is complex, requires new skills and tools, adds additional burden on network management, adds cyber security overheads, etc. Therefore, complexity and overheads reduce many benefits in many applications [34]. A lot of work is still required to address the current issues and challenges in order to make the standard more acceptable and implementable. Better integration tools, interoperability/interchangeability characteristics and better naming convention will definitely enhance the acceptance of the standard, so that it is easily read by every utility. Similarly, device independent and user friendly integration software should be made along with such vendor configuration software which is able to use the created SCL configuration files. Until all of these issues are not addressed, the end user will not be able to enjoy the available interoperability/interchangeability while working with multi-vendor equipment [6]. The next section discusses integrating IoT with IEC 61850.

10. Internet of Things (IoT) and IEC 61850

Internet of things (IoTs) is a communication technology, which makes everything capable of communicating with other things existing in this world such as homes, cars, animals, humans, farms, and industry, etc. A substation has always a large number of Intelligent Electronic Devices (IEDs); therefore, it is considered a natural application for IoT. However, integrating IoT in a substation environment has many challenges. The fundamental concept behind the IoT is that lot of sensors provide data to generate useful information for the required application. Each sensor uses a unique assigned address to feed information through public internet to cloud based applications. But, if the connected devices are huge in number as in a substation, it will require a major change how the addressing of the devices is done. Similarly, use of public Internet to communicate with field devices in a substation raises serious cyber security and Quality of Service (QoS) concerns [36, 37].

Energy sector has also well-defined communications technology and protocols, i.e., DNP3, and IEC 61850, and these protocols are not used in IT, web, and Internet applications. In IoT, most widely used Advanced Message Queuing Protocol (AMQP) supports a transactional model, making it more complex and not appropriate for edge devices. Energy sector protocols typically use a Master/Slave or Client/Server approach. Although, the web uses a client/server approach, but, it is based on a different paradigm and the HTTP protocol used in web is connectionless which also reduces the efficiency. Moreover, the data acquisition approach through Internet and in automation systems is very different. Although, Intel is already proposing a protocol for communication for substation environment, but to achieve true interoperability between different vendors is a big challenge, i.e., necessary for devices and applications to share a common data model. Vendors of networking devices offer Network Management Software (NMS) to support their devices, which is generally designed to support devices from a single vendor. However, the development of a universal management platform remains a challenge, and may not even be economically feasible [36, 37].

Another important challenge of IoT is to get a sense of the large amount of data produced by the sensors. It means that applications will need to be able to figure out the meaning of the data, i.e., the semantics, is the sensor reading voltage or temperature? Also, IoT uses the concept of cloud computing, and vendors are constantly evolving their applications and adding new features to keep up with market and customer requirements in energy sector, but organizations simply cannot afford to keep up with rapid change. IoT also requires extensive computing capability. However, even the smallest utility will face it difficult to maintain the applications and install updates to address bugs or security issues, i.e., extensive computing [36, 37].

The next section presents a case study of substation.

11. Case study of substation in wired and wireless architecture for End-to-End delay measurement of Sample Value (Type 4) messages.

11.1 Wired (Ethernet) topology

A case study was done by making an architecture of the substation in the bus and star topology for the end-to-end delay measurement of the Type 4 messages, i.e., station to process level network simulation model.

11.1.1 Bus topology: MUIED (Merging unit IED), BRKIED (Breaker IED), and PCIED (Process control IED), were designed in the OPNET Modular using object oriented modeling approach. PCIED is generally placed in the bay level and MUIED is generally placed in the process level. MUIED collects data from the process area, i.e., through CT's/PT's and transfers this information to the PCIED for further processing, i.e., sending a trip command to the BRKIED to open or close a breaker accordingly. PCIED is also connected to the central station through the station bus for the data exchange so that central station can perform supervisory actions. The node models (design) of the MUIED and BRKIED for bus topology are shown in Figure 6. The communication stack for the MUIED is very simple, i.e., application layer, Ethernet layer, and physical layer.

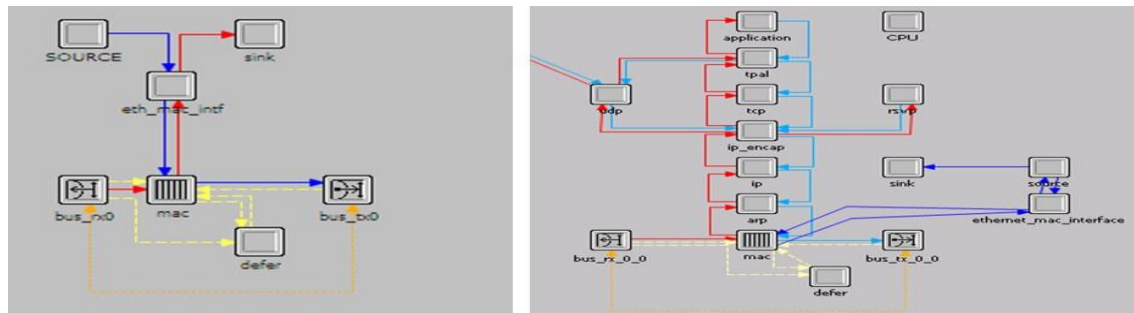


Figure 6. Node model diagram for MUIED (left), and BRKIED (Right) for Bus topology

Figure 7 shows the bus topology architecture of the substation and the end to end delay measurement of the SV messages from the process to station level.

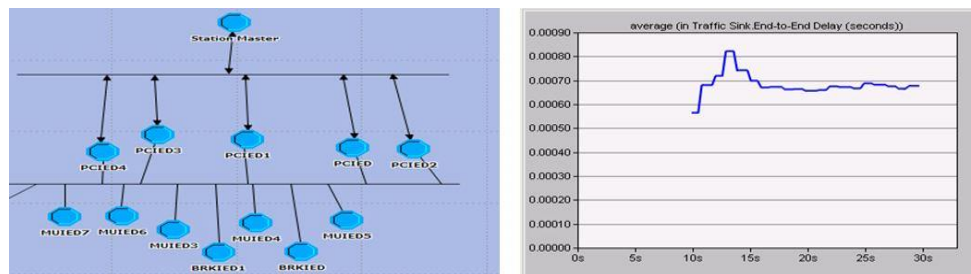


Figure 7. Bus topology architecture from station to process level (left), and SV End-to-End delay measurement

11.1.2 STAR topology: Similarly, MUIED, BRKIED, and PCIED for star topology were designed. Figure 8 shows the star topology architecture of the substation and the end to end delay measurement.

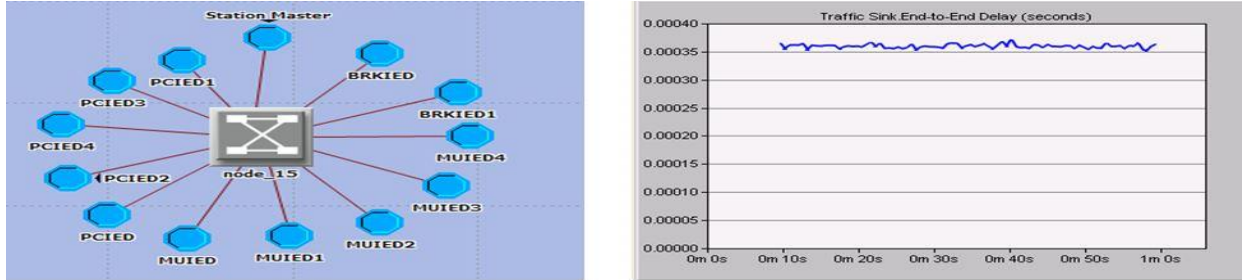


Figure 8. Star topology architecture (left), and SV End-to-End delay measurement (right)

The Ethernet standard IEEE 802.3 has been used with the CSMA/CD (Carrier sense multiple access/collision detection) media access approach for the transfer of data. The table below shows the measured values at different speed and frequency. The raw data source is the simple source with finite state machine.

Table 1. SV message End-to-End delay measurement for Bus and Star topology in wired architecture

LAN Speed (Mbps)	Sample /Sec	Sampled Value message average delay (msec) (Bus Topology)	Maximum delay (msec)	Sampled Value message average delay (msec) (Star Topology)	Maximum delay (msec)
10	480	0.8	1.4	0.3	0.35
10	960	1.0	2.0	0.3	0.37
10	1920	1.2	2.2	0.3	0.35
100	480	0.75	1.3	0.3	0.32
100	960	0.75	1.3	0.3	0.32
100	1920	0.7	1.2	0.3	0.32

Table 1 shows that for bus topology at 10 Mbps, delay increases as the number of samples increases. However, at 100 Mbps, the delay does not increase by increasing the number of samples, and its value is also less as compared to the delay at 10 Mbps. For star topology, the end-to-end delay does not increase with the increase of the samples, and delay is also less as compared to the bus topology. For the bus topology, sometimes stations find the medium busy especially for the case of the low data rate transfer and high number of nodes. The data shows that the end-to-end delay is within the allowed limits of the standard, i.e., 3-4 msec, for the time

critical messages (protection), and automation and metering application messages [16], [17]. This data also shows that it should be avoided to send larger packet size, i.e., samples, to meet the standard guidelines, especially for bus topology at low speed, i.e., 10 Mbps.

11.2 Wireless topology

Even with the advance architecture of the substation, cabling in the substation accounts for large amount of money and complexity, which can be reduced either fully or partly by performing the substation automation functions wirelessly. Therefore, a wireless topology was created as shown in figure 9, and different wireless IEDs (MUIED, BRKIED & PCIED) has been placed in the substation in an ad-hoc mode with no centre access point. The layout (design) of the MUIED for wireless topology is shown is also in Figure 9.



Figure 9. Node model diagram (left) for MUIED, wireless topology architecture (middle), and SV end-to-end delay measurement (right) for wireless topology architecture

Table 2 shows the results for different data rates and for different samples in case of wireless architecture.

Table 2. SV end-to-end delay measurement for wireless architecture

Data Rate (Mbps)	Sample/Sec	Sample Value Message (average delay)	Sample Value Message (maximum delay)
11	50	6 msec	10 msec
11	75	20 msec	80 msec
11	100	0.5 sec	1.0 sec
11	480	2.0 sec	3.0 sec
11	960	2.0 sec	3.0 sec
11	1920	2.0 sec	3.0 sec
54	50	5.0 msec	10.0 msec

54	75	1.0 sec	1.2 sec
54	100	2.5 sec	2.5 sec
54	480	3.0 sec	3.0 sec
54	960	3.2 sec	3.0 sec
54	1920	3.3 sec	3.0 sec

Table 2 shows that for both 11 and 54 Mbps, the delay increases as the number of samples increases. However, the maximum delay is almost the same for different data rates, as the sample size increases. The end-to-end delay for the wireless medium is more as compared to the wired medium. This is due the fact that in wireless medium, electromagnetic interference, radio frequency interference, signal fading, and the attenuation of the signal by bouncing off with the obstacles are the main reasons of the loss of signals. The data also shows that the end-to-end delay is not within the allowed limits of the standard, i.e., 3-4 msec, for the time critical messages, i.e., protection [17]. However, this delay is still within the limits of standard for the automation and metering applications [16].

The results show that for practical applications, the size of the sample should be small to ensure reliable and real time data transmission. The main factors affecting delay are samples per second, communication architecture (bus, star or wireless), and Ethernet link bandwidth. Similarly, for important messages, the specific protection IEDs should be connected on the same Ethernet switches in order to get fast and reliable delivery.

The next section provides an overall discusses.

12. Discussion

All of the issues/challenges have been described in the above sections. First of all, paper presents in detail about the physical issues, i.e., hierarchical, with a detailed analysis for process bus challenges in substation automation system, describing that how much it is important to deal with the hierarchical and topological issues. As process bus takes care of the equipment directly attached to switchyard, therefore any failure in process bus will ultimately affect the whole substation. For a secure and reliable communication within the substation network, Ethernet topology, time critical requirements, selection of the functions and performance requirements, etc., should be selected carefully. Then paper discusses in detail about interoperability and interchangeability issues when there are devices from different manufacturers. The paper describes that interoperability and interchangeability are one of the big challenges for the rapid expansion and growth of IEC 61850.

Similarly, commissioning issues have been discussed, which should be standardized and prepared according to the requirement in advance, as standard is still new. The paper then

presents a detailed analysis of the security issues, i.e., cyber security, logical, and software failures in IEC 61850 based SAS. This issue/failure can cause problems for data communications within SAS and also outside the substation, ultimately affecting the performance of the utility up to the severe level. Software failures and security issues has become a serious challenge to the IEC based SAS as compared to the existing relay based models and require a detailed study and a secure solution. Therefore, an in-depth study and solutions understanding is required before planning a new cyber physical substation infrastructure in order to build a safe and steady power energy source. The paper also discusses manpower skills and training issues for the implementation of SAS in a utility. The paper specifies the importance of workers skills, organizational culture, training and competency levels, etc. for the implementation of IEC 61850 in a utility. The paper finally discusses in detail about the future of IEC 61850 protocols, especially in North American utility, where the standard is still facing a strong competition from DNP 3 protocol. It will take a long time for the IEC 61850 protocol to widely adapt by the utilities, especially if all of these challenges are not addressed.

13. Conclusion

Many papers have been published highlighting the different technical challenges and issues for the IEC 61850 based SAS. However, these papers generally discuss one or two issues, i.e., implementation or interoperability, or cyber security, etc., and do not present a comprehensive and detailed overview of all the challenges and issues. This paper presents a comprehensive overview (all possible issues with detail) of all kinds of technical issues and challenges faced by the IEC 61850 based SAS, i.e., hierarchical structural issues, implementational issues, reliability, interoperability, interchangeability, synchronization, latency, cyber security, commissioning, manpower training and skill, and all other different issues, etc. Moreover, other issues such as good architecture, appropriate redundancy, operational and functional stuff, backup system for high availability, reliability, latency, environmental, sustainability, synchronization, comprehensive testing process, cost, substation expandability, functions allocation, reliable protocols for integration and security, etc. have been discussed in details in this paper. The paper finally also discusses about the future of IEC 61850 protocols, especially in North American utility, where the standard is still facing a strong competition from DNP 3 protocol. The paper also discusses about the challenges of integrating IoT with IEC 61850.

The paper also presents a case study of the measurement of end-to-end delay of SV messages, i.e., type 4, for the wired (bus and star topology) and wireless substation architecture. The results show that the delay is within the limits in case of Ethernet (bus and star) topology, but, the delay is not within limits for wireless topology as defined by the standard due to invariant noise and distance, and other physical factors. Therefore, which medium should be used, i.e., wired or

wireless, can be decided based on the substation environment, utility requirements and keeping in mind of the merits and demerits of both approaches.

Although, IEC 61850 is much more than a protocol, and offers communication services for real time applications, offers metadata among devices and services, multiple information models and a system configuration language, but the paper has presented it clearly that it is not possible to develop a well functional IEC 61850 based SAS without understanding and addressing all these challenges. Addressing these issues and challenges will maintain the consistency throughout the life time of the substation, i.e., checking and verifying during the commissioning process, replacing the failed IEDs, conducting preventive maintenance, and adding new IED to the existing system. The utilities still need time to move to this standard for adaptation, as it is also a big standard, still updating itself increasing its complexity, and efforts (workers training and skill, cost, management issues, utility atmosphere, etc), with all of the above mentioned issues.

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Preparation and Applications of Polythiophene Nanocomposites

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Abstract: Polythiophene (PTh) nanocomposites are unique and attractive materials because of their excellent electrical, electro-chromic and electronic properties with high environmental and thermal stabilities. Polythiophenes and their nanocomposites are gaining importance and use as conducting materials in the industries and in a wide range of potential applications including chemical/optical sensors, light-emitting diodes, display devices, photovoltaics/solar cells, transistors, rechargeable batteries, supercapacitors, EMI shielding etc. A comprehensive review on the preparation of nanocomposites based on polythiophenes using several types of materials such as metal oxides nanoparticles, metal nanoparticles, graphene, carbon nanotubes etc. and their potential applications in various scientific fields have been discussed in this article.

Keywords: Polythiophenes, Nanocomposites, Sensors, *In-situ* polymerization, Photo-catalyst.

الخلاصة: المركبات النانوية من البوليثيوفين (PTh) هي مواد فريدة وجذابة بسبب خصائصها الكهربائية والكهروكرومية والإلكترونية الممتازة ذات الاستقرار البيئي والحراري العالي. تكتسب البوليثيوفين ومركباتها النانوية أهمية واستخدامها كمادة موصلة في الصناعات وفي مجموعة واسعة من التطبيقات المحتملة بما في ذلك أجهزة الاستشعار الكيميائية / البصرية، الثنائيات الباعثة للضوء، أجهزة العرض، الخلايا الكهروضوئية / الخلايا الشمسية، الترانزستورات، البطاريات القابلة لإعادة الشحن، المكثفات الفائقة، EMI التدريع وما إلى ذلك. تمت مراجعة شاملة حول تحضير المركبات النانوية على أساس البوليثيوفين باستخدام عدة أنواع من المواد مثل الجسيمات النانوية أكاسيد المعادن، والجسيمات النانوية المعدنية، والجرافين والأنابيب النانوية الكربونية وما إلى ذلك. ومناقشة تطبيقاتها المحتملة في مختلف المجالات العلمية.

1. Introduction

Conducting polymers (CPs) and their nanocomposites (NCs) are particularly interesting materials for a number of applications like structural, electronic, thermal, electrochemical, electromagnetic interference shielding (EMI) etc. either in the partially oxidized or in the reduced state. Conducting polymers have extended π -systems and are highly susceptible to chemical or electrochemical oxidation or reduction. Thus the electrical and optical properties of such polymers could precisely be altered by controlling carefully the process of oxidation and/or reduction. Since these reactions are often reversible, it is possible to systematically control the electrical and optical properties with a great deal of precision switching from a highly insulating state through semiconducting to the highly conducting state with greater thermal stability. Thus conducting polymers can be perceived as macromolecules having the fully conjugated sequence of bonds along the backbone which acquires a positive or negative charge by oxidation or reduction process [1-6].

With the advent of many more discoveries in the field of conducting polymers, today we have a variety of polymers which have shown to exhibit electrical conductivity. Currently, conducting polymers (CPs) such as polypyrrole (PPy), polyaniline (PAni), polythiophene (PTh) and their derivatives are promising materials for the preparation of nanocomposites (NCs) materials and the devices based on them. Nanocomposites are a special class of materials originating from suitable combinations of two or more such nanoparticles or nanosized objects resulting in materials having unique properties and the wide application potential in diverse areas. Novel properties of nanocomposites can be derived from the successful combination of the characteristics of parent constituents into a single material [7-18].

Many investigations regarding the development of the incorporation techniques of the nanoparticles into the polymeric matrices have been published [19]. In most of the cases, such combinations require blending or mixing of the components, taking the polymer in solution or melt form [20]. Resulting nanocomposites have found successful applications in versatile fields viz. battery cathodes [21], microelectronics [22], nonlinear optics [23], sensors [24] etc. Among conducting polymers composites, the polythiophene nanocomposites have received much more attention from scientific communities and researchers in recent years because of their unique electrical, electro-chromic and electronic properties with high environmental and thermal stabilities [25–27]. Polythiophenes and their nanocomposites are the important and most frequently used CPs in the industries with a wide range of potential applications including chemical & optical sensors, light-emitting diodes (LEDs), display devices, photovoltaic solar cells and transistors [28-29].

As a result, a large number of papers on PTh nanocomposites have been published in recent times. The present review summarizes the systematic progress in the preparation and applications of polythiophene nanocomposites in the field of sensor, photocatalyst, rechargeable batteries, supercapacitors and EMI shielding etc. For the convenience of

readers, the present discussion is divided into several categories depending upon the composite materials and the application aspects. We hope this article will provide the readers a better understanding of the recent developments and advancements of polythiophene nanocomposites research.

2. Preparation of Polythiophene Nanocomposites

The synthetic strategies for the preparation of nanocomposites play a very important role as they impinge upon the resulting product in terms of morphology and properties and consequently their applications. Most of the methods that are in use for nanocomposites preparation are generally based on two routes: (i) one-step redox reactions where simultaneous polymerization of CPs and formation of nanoparticle takes place or (ii) *in-situ* polymerization where pre-synthesized nanoparticles are mixed into the monomer solution followed by chemical or electrochemical polymerization.

Chemical reactions usually produce powdery nanomaterials in bulk and can easily be scaled up. On the other hand, electro-polymerization restricts the reactions on the surfaces of electrodes; results in films of the composites deposited on the electrode surface. Thus it is difficult to get a large amount of nanomaterial by electrochemical techniques and the composition and property of the nanomaterials changed slightly during the electrochemical growth process, especially in the case of long-time electrodeposition. This is mainly due to the surface morphology and resistance of the working electrode continuously changing with increase in film thickness. Therefore, the electrochemical technique is usually chosen for the purposes of synthesizing nanocomposites with controlled morphologies and fabricating micro-sized or thin-layer devices. In addition, electrochemical polymerisation has a number of well-known advantages because the electrochemical variables can be adjusted to control the film thickness and other characteristics of the polymer nanocomposite films.

2.1 Nanocomposites of polythiophene with metal oxide nanoparticles

In-situ chemical polymerization is the most commonly employed method because it provides a better size and shape control than the one-step redox method. Biswas *et al.* [30] successfully prepared polythiophene (PTh) and PTh/Al₂O₃ nanocomposite in bulk and in solution (chloroform) via chemical oxidative polymerization using FeCl₃ as oxidant and they observed higher yield in the later case. They observed that the high yield of PTh (70–80%) could be achieved when thiophene was added to FeCl₃ solution directly at temperatures above 60°C. The results showed that the conductivities of PTh and PTh/Al₂O₃ nanocomposite were of the order of 10⁻³ S cm⁻¹ for both the I₂ doped samples.

Martin *et al.* [31] synthesized PTh/TiO₂ nanocomposite via *in-situ* chemical polymerization having core-shell morphology. They investigated the electrochemical and photoelectrochemical properties of the nanocomposite.

Xu *et al.* [32] synthesized SnO₂ hollow spheres (hs)/polythiophene hybrid materials by an *in-situ* chemical oxidative polymerization method. TEM micrographs of hs-SnO₂ and hs-

SnO₂/(20%)PTh hybrids showed that the hs-SnO₂ was successfully synthesized with an average size of about several hundred nanometres and had a rough morphology. It was observed that hs-SnO₂ particles got encapsulated partly by PTh.

Huang *et al.* [33] also synthesized PTh/WO₃ nanocomposites by *in-situ* chemical polymerization method. By TEM micrographs of pure WO₃ and PTh/WO₃ hybrid, it was observed that the WO₃ has an average particle size of about 20–30 nm and WO₃ particles were well encapsulated by PTh with a thickness of about several nanometres. Thermal stability of the hybrids was examined by TG analysis. In the case of pure PTh, the mass decrease started at approximately 290°C and almost decomposed completely when the temperature was up to 650°C. Different from pure PTh, the 10 wt% PTh/WO₃ hybrid was initially stable up to 320°C which was 30°C higher than the pure PTh. The delay of the decomposition process of the hybrid indicates that the thermal stability of the PTh/WO₃ hybrid is better than that of the pure PTh.

Barkade *et al.* [34] prepared PTh/SnO₂ nanocomposite via ultrasound-assisted *in-situ* chemical oxidative polymerization by using anhydrous FeCl₃ as the oxidant and dopant in batch mode. By TEM image, it was observed that all SnO₂ nanoparticles got encapsulated by PTh and no uncovered SnO₂ nanoparticles were observed. The SnO₂ nanoparticles were uniformly dispersed in PTh. This can potentially be attributed to the ultrasonic irradiation used during polymerization which may break the aggregation of SnO₂ nanoparticles.

Tahmasebi *et al.* [35] has successfully modified the surface of Fe₃O₄ NPs by polythiophene using self-assembly of polythiophene onto Fe₃O₄ NPs via oxidative polymerization of thiophene monomers in the presence of Fe₃O₄ NPs and using KMnO₄ as oxidant. They reported their application as a new sorbent in magnetic solid-phase extraction (MSPE) for extraction and preconcentration of plasticizer from real water samples. They observed that the coating of NPs with polythiophene can increase the adsorption ability of the target analytes, improve stability of the NPs and their dispersibility in aqueous media.

Khatamian *et al.* [36] synthesized the nanocomposites of polythiophene (PTh)/zinc oxide (ZnO) nanoparticles with different PTh wt%, (2%, 4%, 6%, 10% and 20%) by an *in-situ* chemical oxidative polymerization method. They evaluated photocatalytic activities of the nanocomposites by the degradation of methyl orange (MO) aqueous solution under visible light and sunlight irradiation. They observed that at a higher percentage of PTh, the photodegradation activity was improved because of high adsorption capacity.

2.2 Nanocomposites of polythiophene with graphene and carbon nanotubes (CNTs)

Graphenes are atom-thick layers of carbon exhibiting exceptional properties. These layers or sheets when rolled at specific chiral angles form carbon nanotubes (CNTs). CNTs possess extremely high aspect ratio and show extraordinary thermal, electrical and mechanical properties which are dependent on the rolling angle and radius. When incorporated into PTh, they improve the properties and also render them useful in various applications.

Karim *et al.* [37] successfully synthesized polythiophene (PTh)/single-wall carbon nanotubes (SWNTs) nanocomposites by the *in-situ* chemical oxidative polymerization method. The structure and properties of the nanocomposite (PTh/SWNT) were characterized with elemental analysis, x-ray photoelectron spectroscopy, Raman spectroscopy, Fourier transform infrared, ultraviolet-visible spectroscopy, field emission scanning electron microscopy, thermogravimetric analysis, x-ray diffraction and transmission electron microscopy. TEM photograph showed the tubular morphology of the PTh/SWNT nanocomposite. SWNTs were used as self-assembly hard templates for the formation of one-dimensional, co-axial PTh/SWNT nanocomposite. The polymer was found to be tightly coated only on the surface of the SWNTs. By comparing TEM photographs of the pure SWNTs with the PTh/SWNT nanocomposite, it was concluded that nanocomposite was very thick (60–80 nm in diameter) and the surface was not smooth. Field emission scanning electron microscopy and transmission electron microscopy analysis revealed that the PTh/SWNT nanocomposite as core (SWNTs) and shell (PTh) hybrid structures. They reported that the electrical conductivity of resulting PTh/SWNT nanocomposite is $\sim 0.41 \text{ Scm}^{-1}$ at room temperature which is greater than the conductivity of pure PTh $\sim 1.67 \times 10^{-6} \text{ Scm}^{-1}$ synthesized under identical conditions.

In another study, Yusuf *et al.* [38] prepared polythiophene and single-walled carbon nanotube (PTh/ SWCNT) nanocomposite by chemical oxidative polymerization using anhydrous ferric chloride as oxidant and chloroform as solvent. Comparison of PTh and PTh/SWCNT nanocomposites by SEM, the presence of a random network of interconnected bundles packed underneath the outermost polymer pellet in the PTh/SWCNT nanocomposite. The observed conductivity of PTh/SWCNT nanocomposite was found four times greater than that of polythiophene and the real part of the permittivity (ϵ) of PTh/SWCNT nanocomposite was much higher than that of pure polythiophene. Further, it was observed that the electrical behaviours of PTh could be modified by employing single-walled carbon nanotubes and also a semiconducting peculiarity of these nanotubes bring a semiconductor-like polymer nanocomposite.

Lee *et al.* [39] synthesized nanocomposites of conducting polythiophene with the host filler multi-walled carbon nanotubes (MWNTs) by the *in-situ* γ radiation-induced chemical polymerization method at room temperature. The resultant morphology of the nanocomposite (PTh/MWNT) structures was characterized by field emission scanning electron microscopy with the energy dispersive spectroscopy, Fourier transform infrared, thermal gravimetric analysis, x-ray photoelectron spectroscopy and transmission electron microscopy. The morphology observed by transmission electron microscopy of the MWNT and PTh/MWNT nanocomposite was tubular. Also, interfacial entrapment between the PTh and MWNT showed the polythiophene is coated on the surface of the carbon nanotube. It was found that the tubular inner part was mainly the compound of MWNT and the outer coated surface was

conducting polythiophene with the variable thicknesses (20–50 nm diameter) and their surfaces are not smooth. PTh/MWNT nanocomposite showed improved thermogravimetric stability as compared to PTh upto 800°C. The conductivity of the samples was measured by standard four-point probe methods. The conductivity of the PTh/MWNT nanocomposite was found to be 3.71 Scm^{-1} which is much larger than the usual value of the PTh ($\sim 1.23 \times 10^{-4} \text{ Scm}^{-1}$).

Wang *et al.* [40] have successfully prepared different polythiophene/multiwall carbon nanotube (MWNTs) nanocomposite with 30 wt% and 50 wt% MWNTs by solution mixing (PML), mechanical ball milling (PMM) and *in-situ* composite (PMI). They investigated the morphology, internal structure and thermal stability of the nanocomposites by SEM, XRD, FTIR and TGA. The electric conductivity and Seebeck coefficient of the bulk nanocomposites were simultaneously measured using a Seebeck coefficient/electric conductivity measuring system from room temperature to 393K in the helium atmosphere. Thermal conductivity was also measured by thermal conductivity tester KY-DRX-RW. The nanocomposites prepared by solution mixing (PML) exhibited highest Seebeck coefficient and highest electrical conductivity among those of the composites prepared by these three methods: solution mixing (PML), ball milling (PMM) and *in-situ* composite (PMI). The MWNTs in the composites prepared by PML were better dispersed in the polymer matrix than those in the composites prepared by PMM which leads to higher conductivity. More interfaces between PTh and MWNTs in the nanocomposite prepared by PML due to the better dispersing of MWNTs which leads to higher Seebeck coefficient. However, the nanocomposites prepared by PML showed higher Seebeck coefficient and higher electrical conductivity due to the core-shell PTh-MWNT microstructure formed during the *in-situ* oxidative polymerization of PTh. The MWNTs were coated with PTh and could directly not touch each other leading to its lower conductivity. The results showed that the MWNTs were uniformly dispersed in the polymer matrix and the nanocomposite materials exhibited good thermal stability under 200°C. The TGA results indicated that the thermoelectric properties of the composites could be investigated under 200°C without destroying the structures of PTh. The electrical conductivity for the nanocomposites improves greatly from 2.34 Sm^{-1} to 29.82 Sm^{-1} with increasing the MWNTs content from 10 wt.% to 90 wt.%. The highest conductivity of 29.82 Sm^{-1} is 11 times higher than that of pure PTh. With increasing MWNTs content, the Seebeck coefficient slightly fluctuates, the thermal conductivity slightly increases but the electrical conductivity increases remarkably. From the results, this work suggests that the polymers with high Seebeck coefficient will play an important role in improving thermoelectric performance of polymer/inorganic nanocomposites.

Bora *et al.* [41] reported a new method for the synthesis of polythiophene (PTh)/graphene oxide (GO) nanocomposites by liquid/liquid interfacial polymerization. Polymerization occurred at the interface of two immiscible solvents i.e. *n*-hexane containing thiophene and nitromethane containing GO and an initiator. They observed that PTh/GO nanocomposites

exhibited improved thermal stability compared to pure PTh. Both the optical and electrochemical band gap of the nanocomposites found to decrease dramatically on the incorporation of GO into the polymer matrix. Electrical conductivity and the specific capacitance value of the composites was found to be $2.7 \times 10^{-4} \text{ Scm}^{-1}$ and 99 Fg^{-1} respectively. By the result obtained they concluded that the PTh/GO nanocomposites prepared using the interfacial polymerization method possessed great promise for a range of potential applications in batteries and optoelectronic devices.

Swathy *et al.* [42] have synthesized the polythiophene-multi walled carbon nanotubes nanocomposites (PTh-CNTs) by *in-situ* chemical oxidative polymerization of thiophene in presence of multiwalled carbon nanotubes using ferric chloride as an oxidizing agent and sodium bis-2-ethylhexylsulfosuccinate (AOT) as an anionic surfactant in chloroform solvent.

2.3 Nanocomposites of polythiophene with multi-component systems

Xie *et al.* [43] have successfully synthesized La-doped barium-ferrite/polythiophene (LB/PTh) nanocomposites by *in-situ* chemical oxidative polymerization. Morphology was investigated by transmission electron microscopy (TEM) and scanning electron microscopy (SEM). Electromagnetic properties of nanocomposites were tested by four-probe conductivity tester and vibrating sample magnetometer (VSM). The results of XRD indicated that La^{3+} had entered into the lattice of barium ferrite. TEM and SEM studies showed that the nanocomposites have a core-shell structure. SEM images revealed that PTh is deposited on the surface of LB particles which have a nucleating effect on the polymerization of PTh. TEM images also indicated that the ferrite particles are embedded in PTh matrix forming the core-shell structure. The black core is magnetic ferrite particle and the light-coloured shell is PTh in the nanocomposite due to the different electron penetrability. It indicates that the nanocomposite is composed of polycrystalline LB ferrite particles and PTh which is in accordance with the results obtained by FT-IR analysis. It was observed that the electrical conductivity of the nanocomposite decreases with increasing the ferrite particles content. There may be two main reasons for the decrease in electrical conductivity. The first reason may be the insulating behaviour of ferrite particles in the core of nanocomposite hinders the charge transfer in PTh. While the other may be the generation of the stable σ - π bond between PTh and ferrite particles decreases the conjugated π -electron density in PTh. It was also revealed that the nanocomposites showed the hysteretic loops of the ferromagnetic behaviour under the applied magnetic field.

Ge Ma *et al.* [44] successfully synthesized Cu-doped zinc oxide and its polythiophene nanocomposites by the Sol-Gel and *in-situ* polymerization methods respectively. The antibacterial results reveal that the CZ/PTh nanocomposites possess better antibacterial activity compared with CZ because of the photosensitization of PTh to CZ. The antibacterial activity of composites improves with the contents of CZ increasing and there exists certain synergistic antibacterial effect between PTh and CZ instead of mixing CZ and PTh simply.

The metal-ion and nanoparticles can improve the antibacterial efficiency together in which photocatalytic mechanism is the most persuasive among them. The result showed that the conductivity of CZ is much higher than those of ZnO and CuO and the conductivities of CZ/PTh nanocomposites are also higher than those of CZ and PTh. It is because the band gap of CuO (1.70 eV) is much narrower than that of ZnO (3.37 eV).

Wang *et al.* [45] prepared polythiophene/Pd/TiO₂ (PTh/Pd/TiO₂) ternary composite microspheres and applied such a composite to photoelectrochemical (PEC) sensing. TiO₂ spherical aggregates of 200 nm diameter consisting of nanoscale building blocks of TiO₂, have been prepared by hydrolysis of tetrabutyltitanate in a water-in-oil emulsion system ($V_{\text{water}}/V_{\text{acetone}}=1/100$). Pd species and PTh layer were decorated onto TiO₂ microspherical substrates by reduction of Pd salts and polymerization of thiophene respectively. The high surface area, effective charge transfer and enhanced light absorption of the ternary composite could improve PEC performance under simulated sunlight. The sensitivity, selectivity and stability of the PEC sensor for detecting L-cysteine were much higher than those of the traditional electrochemical sensor. The detection limit of L-cysteine was 9.24 μM in the linear range of 0.31–5.30 mM. Moreover, the results also indicated a good anti-interference and acceptable accuracy in practical application providing a rapid and sensitive detection method.

Mehdinia *et al.* [46] successfully synthesized a magnetic nanocomposite of G/Fe₃O₄/PTh by *in-situ* chemical polymerization. The prepared nanocomposites were used as a novel sorbent for the magnetic solid-phase extraction of polycyclic aromatic hydrocarbons from environmental water samples.

Chandra *et al.* [47] prepared PTh/TiO₂-Cu composite by a sol-gel process. In another study, Chandra *et al.* [48] synthesized polythiophene supported tin-doped titanium nanocomposites (PTh/Sn-TiO₂) by the modified sol-gel process through oxidative polymerization of thiophene. They reported that polythiophene acts as good sensitizer towards LPG and supporter for the tin-doped titania that improve the photocatalytic activity under visible light.

2.4 Nanocomposites of polythiophene with metal nanoparticles

Bagheri *et al.* [49] synthesized a nanocomposite consisting of polythiophene with a silver (PTh/Ag) by chemical oxidative polymerization in the presence of anhydrous ferric chloride and implemented as a desired sorbent for headspace needle trap extraction. They observed that the presence of Ag NPs within the polymeric structure could be responsible for higher specific surface area and sorption capacity while the PTh moiety contributes to the hydrophobic and π - π interactions. The synthesized nanocomposite was conveniently implemented to the isolation of some selected PAHs from different water samples.

Shanmugapriya *et al.* [50] synthesized the polythiophene (PTh) via *in-situ* chemical polymerization method. Conducting polythiophene (PTh) was blended with micro copper (μ -Cu) and nanocopper doped polythiophene (n-Cu) by mechanical mixing. The room

temperature electrical conductivities of PTh, μ -Cu/PTh and n-Cu/PTh were calculated and found to be $7.2 \times 10^{-4} \text{ Scm}^{-1}$, $2.8 \times 10^{-3} \text{ Scm}^{-1}$ and $1.0 \times 10^{-2} \text{ Scm}^{-1}$ respectively. The result revealed that there is an increase of one order in electrical conductivity in the micro composite and two order of increase in electrical conductivity in the nanocomposite when compared to pristine PTh. The improvement in the electrical conductivity of these composites is expected to enhance the application potential of the polymer composites.

3. Applications of Polythiophene Nanocomposites

Polythiophene nanocomposites have been used for many applications due to their chemical, mechanical, optical and electrical properties. Their semiconductor properties allow conjugated polymers to be used particularly in a large area, such as electrochromic devices (EDCs), rechargeable batteries, light-emitting diodes (LEDs), field-effect transistors (FETs), photovoltaic cells and chemical Sensors.

3.1 Sensors

Kong *et al.* [51] studied the sensitivity test of PTh/SnO₂ composites *viz.* [PTh(1%)/SnO₂, PTh(5%)/SnO₂, PTh(10%)/SnO₂, PTh(20%)/SnO₂ and PTh(30%)/SnO₂] to methanol (MeOH), ethanol (EtOH), acetone and NO_x carried out at room temperature, 50°C, 70°C and 90°C. It was found that PTh/SnO₂ composites with different PTh mass percent could exhibit high sensitivity to NO_x but no sensitivity to 10 ppm, 50 ppm, 100 ppm, 150 ppm and 200 ppm MeOH, acetone and EtOH. It was also observed that the sensitivity increased with the increase of NO_x concentration. It was found that PTP/SnO₂ composites had better selectivity and higher sensitivity than PTh and SnO₂ at much lower working temperature. The PTh/SnO₂ nanocomposites responded to NO_x at a concentration as low as 10 ppm. Polythiophene behaved as a *p*-type semiconductor and SnO₂ as an *n*-type semiconductor. So the composites contained the properties of the *p-n* junction.

In another study, Xu *et al.* [32] reported that the gas sensor based on SnO₂ hollow spheres/PTh exhibited higher gas response, good response and shorter recovery time for detecting NO₂ of ppm levels at low temperature than the sensor based on pure PTh. With increasing the NO₂ concentration and PTh contents, the gas response of the hybrids (10%, 20% and 40%) can be improved.

Barkade *et al.* [34] also reported that PTh/SnO₂ hybrid sensors could detect liquefied petroleum gas (LPG) with high sensitivity at room temperature. PTh/SnO₂ hybrid composite containing 20wt% SnO₂ showed the maximum sensitivity at room temperature.

Uygun *et al.* [52] reported that PTh/SiO₂ nanocomposites can be used for the fabrication of novel glucose biosensors with the rapid response time. The amperometric response of enzyme-coated electrodes to glucose was enhanced when the surfactant was present in the preparation of the nanocomposites. The highest linear range from 0.06 to 1.585 mM of glucose was determined for the PTh/SiO₂/Tween-20 electrode. They concluded that the

response time of the electrode prepared in the presence of surfactants was from the 30s to 50s while the response time for a surfactant-free PTh/SiO₂ electrode was about 70s.

Huang *et al.* [33] demonstrated that the gas sensor based on the PTh/WO₃ hybrids has a high response and good selectivity for detecting NO₂ of ppm level at low temperature. Both the operating temperature and PTh contents have an influence on the response of PTh/WO₃ hybrids to NO₂. The 10 wt% PTh/WO₃ hybrid showed the highest response at a low operating temperature of 70°C.

Tripathi *et al.* [53] successfully synthesized Al₂O₃/polythiophene nanocomposites by chemical oxidation polymerization method. They observed the sensing properties of pure and Al₂O₃/PTh nanocomposites at room temperature. It was found that the sensitivity increases with increase in dopant concentration as well as increase in the analyte gas i.e. ammonia concentration. Response and recovery times for these samples have also been measured. The response and recovery time for 8 wt% of Al₂O₃/PTh showed a significant result. The present study suggests that Al₂O₃ doped polythiophene nanocomposites pellets with proper dopant concentration can be used as a sensing material for ammonia.

Bai *et al.* [54] successfully synthesized nanocomposite of ethylenediamine modified-reduced graphene oxide (RGO) and polythiophene (PTh) by *in-situ* chemical polymerization under room temperature for 2 h. They investigated the sensing response of nanocomposites towards NO₂ gas. The response of the hybrid with 5wt% RGO achieves nearly 4 times higher response than that of pure PTh at room temperature. The hybrid is loaded on a flexible PET thin film to structure a smart sensor. The sensor not only exhibits high sensitivity, good selectivity to NO₂ but also has flexible, simple and inexpensive characteristics which will open a new window to develop a kind of portable and wearable electronic devices to detect hazardous gases in the environment.

3.2 Photocatalysis

Zhu *et al.* [55] synthesized PTh/TiO₂ nanocomposite for the photocatalytic degradation of methyl orange (MO) dye under UV light irradiation. They used a self-designed UV-irradiation instrument with 10W germicidal lamps with a maximum wavelength of 253.7 nm for the catalysis process. Absorbance was measured by a UV-vis spectrophotometer that was used to measure the change in the MO concentration. It was observed that nanocomposite absorbs in the wavelength range of 200-800 nm compared to TiO₂ which absorbs only in the 400 nm region. This suggests that the PTh/TiO₂ nanocomposite can be excited by solar light. It was also observed that in addition to the photodegradation phenomenon, the PTh/TiO₂ nanocomposite allows surface adsorption of the dye which changes with the PTh to TiO₂ weight ratio. With the increase in PTh ratio, the adsorption capacity of the PTh/TiO₂ nanocomposites increases first and decreases afterwards which is related to the structural features of the nanocomposite system. When tested under UV light illumination, the pure PTh used as a catalyst did not show any appreciable degradation of MO (< 5.0%). Pure TiO₂

induced 48.5% MO degradation whereas PTh/TiO₂ showed 56.6% degradation. The rate of degradation initially starts at a high pace after which it becomes stable due to the adsorption of dye on the active sites of the catalyst. PTh/TiO₂ with a higher PTh content exhibited limited catalytic activity. This is because PTh adsorbed on the surface of TiO₂ occupied most of the surface-active sites of TiO₂ thereby preventing the MO molecule from reaching the active sites of TiO₂ for degradation. The surface property is an important factor for the photocatalytic properties and is closely related to the PTh to TiO₂ weight ratio.

In another development, Li *et al.* [56] reported that with increasing PTh content from 0 to 2%, the adsorption capacity of the PTh/TiO₂ composites towards MO increases. Zeta-potential studies showed that the surface of the TiO₂ is negatively charged while the surface of the PTh/TiO₂ composites is positively charged in the dispersion. Therefore, MO is barely adsorbed on the TiO₂ surface due to Coulombic repulsion. On the other hand, the positively charged surface of the PTh/TiO₂ composites can adsorb MO strongly which would contribute to the high photodegradation efficiency due to efficient interfacial charge transfer.

Chandra *et al.* [47] also reported that the PTh/TiO₂-Cu composite prepared by a sol-gel process showed a strong interaction between the interface of PTh and TiO₂-Cu. The TiO₂-Cu composite showed absorption in the region, 450- 500nm. On the other hand, an extension of the absorption regions in the PTh/TiO₂-Cu composite also indicates strong interactions between PTh and TiO₂-Cu. It is expected to accelerate photo-induced charge transfer from the PTh to TiO₂-Cu, and subsequent enhancement of the photocatalytic efficiency of the catalyst. When tested for the degradation of rhodamine blue (RhB), the rate of RhB degradation increased as the PTh content in TiO₂-Cu was increased from 0.5 to 2.0 wt.% reaching a maximum at polymer loading of 1.0 wt.%, and decreasing with further increases in polymer loading to 2.0 wt.%. This shows that there is some specific threshold for PTh to exhibit the optimal catalytic properties in the composite system. The experiment also showed that the concentration of PTh in TiO₂-Cu played a significant role in enhancing the photocatalytic activity. The change in pH alters the charge on the catalyst which affects the adsorption and desorption of the dyes on the catalyst surface. For PTh/TiO₂-Cu, the photocatalytic rate also increased with increasing pH.

3.3 Secondary Batteries

Jung *et al.* [57] reported the synthesis of a Ag/poly(3,4-ethylenedioxythiophene) (PEDOT) nanocomposites through polymerizing 3,4-ethylenedioxythiophene (EDOT) and reducing Ag(I) acetate into neutral Ag via a simultaneous one-pot method. It was observed that Ag/PEDOT nanocomposites were formed as a core-shell structure keeping Ag nanoparticles well dispersed in PEDOT polymer with high surface area and high electrical conductivity. They investigated electrochemical characteristics by galvanostatic discharge/charge and cyclic voltammetry (CV). The charge capacity in the initial cycle for Ag/PEDOT nanocomposites showed 291 mAh/g and also that in the 20th cycle was the highest with 209

mAh/g among the other samples. The morphology of Ag/PEDOT nanocomposites makes Li-ions transfer easier and this results in the enhanced electrochemical performance because of sufficient charge transfer in the interface and convenient mass transfer. The discharge-charge properties of the samples were measured at a current density of 0.5 mA/cm^2 and a voltage from 0.02 to 2.8 V. The CV of the cell was performed over the voltage range, 0 to 2.8 V, at a scan rate of 0.05 mV/s . Ag/PEDOT core-shell nanocomposites for an anode material were prepared by the one-pot reduction method in order to increase the high surface area. The introduction of PEDOT as a good buffering agent to Ag particles prevents Ag particles from being agglomerated, to improve the dispersion of Ag particles and to make Ag particles more stable.

3.4 Supercapacitors

Melo *et al.* [58] reported that composites of polythiophene (PTh) and graphene (GR) with different mass proportions were studied for their application as supercapacitors. They evaluated the electrochemical behaviour of these composites by means of cyclic voltammetry and specific capacitance curves were derived from these measurements. The Faradaic impedance spectroscopy response of the different composites along with that of GR was also studied. From these measurements, it was found that a 1:1 in a mass composite of GR and PTh showed a higher specific capacitance even when compared with GR alone. The introduction of the GR in that proportion also showed enhanced cyclic stability in comparison with the sole polymer. The high specific capacitance (365 Fg^{-1} at 1 Ag^{-1}) of this composite material indicates its potential for use as an electrode material for supercapacitors. The supercapacitor performances of the resulting materials were tested and compared with each other. The specific capacitance of the best composite can reach 365 Fg^{-1} at a discharge current density of 1 Ag^{-1} which is much larger than the value achieved using pure PTh (92 Fg^{-1}). The mixture when prepared with certain ratios of GR and conducting PTh may open the opportunity to prepare low-cost high-performance electrode materials for supercapacitor applications.

3.5 EMI Shielding

Najar *et al.* [59] successfully prepared nanocomposite of polythiophene (PTh) with the photo-adduct of sodium pentacyanonitrosylferrate(II) dehydrate and hexamine is synthesized by *in-situ* polymerization technique. They reported that dielectric studies showed the dielectric constant of the order of 2×10^4 at 10^4 Hz and an AC conductivity of 10^{10} Scm^{-1} of nanocomposite. Due to the high value of dielectric constant and AC conductivity, the nanocomposite can be very useful for EMI shielding applications.

A few review articles on the selective aspects of polythiophene based nanocomposites have also been published [60,61].

Table. 1 Summarized details on preparation and applications the polythiophene based nanocomposites.

S.No.	Nanocomposites	Method of Preparation	Applications	References
1.	PTh/Al ₂ O ₃	Chemical/Oxidative	Electrical Conductor	[30]
2.	PTh/TiO ₂	Chemical/Oxidative	-	[31]
3.	PTh/SnO ₂	Chemical/Oxidative	NO ₂ Sensor	[32]
4.	PTh/WO ₃	Chemical/Oxidative	NO ₂ Sensor	[33]
5.	PTh/SnO ₂	Chemical/Oxidative	LPG Sensor	[34]
6.	PTh/Fe ₂ O ₃	Chemical/Oxidative	Sorbent for Solid-Phase Extraction	[35]
7.	PTh/ZnO	Chemical/Oxidative	Photocatalyst	[36]
8.	PTh/SWCNT	Chemical/Oxidative	Conductor	[37,38]
9.	PTh/MWNT	Chemical/Oxidative	Conductor	[39,40,42]
10.	PTh/GO	Interfacial Polymerization	Conductor and Capacitor	[41]
11.	PTh/La-Doped Barium-Ferrite	Chemical/Oxidative	Electrical Conductor	[43]
12.	PTh/Cu-Doped Zinc Oxide	Chemical/Oxidative	Photocatalyst	[44]
13.	PTh/Pd/TiO ₂	Chemical/Oxidative	Sensing	[45]
14.	PTh/G/Fe ₃ O ₄	Chemical/Oxidative	Magnetic-Solid Phase-Extraction	[46]
15.	PTh/TiO ₂ -Cu	Chemical/Oxidative	Photocatalyst	[47]
16.	PTh/Sn-TiO ₂	Chemical/Oxidative	Photocatalyst	[48]
17.	PTh/Ag	Chemical/Oxidative	Isolation of Selected PAHs from Water Samples	[49]
18.	PTh/Cu	Chemical/Oxidative	Electrical Conductor	[50]
19.	PTh/SnO ₂	Chemical/Oxidative	Sensor	[51]
20.	PTh/SiO ₂	Chemical/Oxidative	Glucose Sensor	[52]
21.	PTh/Al ₂ O ₃	Chemical/Oxidative	Ammonia Sensor	[53]
22.	PTh/RGO	Chemical/Oxidative	NO ₂ Sensor	[54]
23.	PTh/TiO ₂	Chemical/Oxidative	Photocatalyst	[55,56]
24.	PEDOT/Ag	Chemical/Oxidative	Secondary Batteries	[57]
25.	PTh/Graphene	Chemical/Oxidative	Super Capacitor	[58]
26.	PTh/ Na ₂ [Fe(CN) ₃ (OH)(NO)(C ₆ H ₁₂ N ₄)]H ₂ O	Chemical/Oxidative	EMI Shielding	[59]

4. Conclusions and Scope for Future Work

Nanocomposites of PTh show better electrical, mechanical, optical, thermal etc. properties as compared to pure PTh. However, in many cases, the secondary component also tends to reduce its electrical conductivity. In this review, we have summarized the various techniques applied for the preparation of PTh nanocomposites and the fabrication of devices for potential applications including chemical sensor, optical sensors, light-emitting diodes (LEDs), display devices, photovoltaics/solar cells, transistors, rechargeable batteries, supercapacitors, EMI shielding etc. The multi-functionality of PTh nanocomposites have been extensively exploited in diverse applications with impressive results. The synergistic effects between the

constituents have made these materials particularly attractive as sensing elements for gases. Efforts are on towards understanding the working mechanism of PTh nanocomposites which will increase their potential fields of applications.

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6. References

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A Review on the Advances in Design of Exhaust Gas Recirculation (EGR) for Diesel Engine

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Abstract: Diesel engine is one of the enormously used technologies in mobile and stationary application. Although, this enormous use boomed the economic development but it also caused serious environmental hazards. Diesel engine uses combustion phenomenon that gives birth to SO_x , NO_x , soot particles and other dangerous compounds. Exhaust Gas Recirculation (EGR) technology was developed to control the emission of NO_x . EGR technology today is not as it was a few decades ago. It evolved with the passage of time. The study of evolution in previous two and half decades is the scope of this review paper. Work on the control and sensing technology is also discussed but major scope of this paper is to review advances in EGR technology from mechanical perspective. Addition of new components along the timeline in the choronological sequence is briefly described. An effort is made to gauge the work in different areas and to direct future work to improve EGR technology.

Keywords: diesel engine, exhaust gas recirculation, soot particles, NO_x , SO_x

الخلاصة: محرك الديزل هو أحد التقنيات المستخدمة بكثرة في التطبيقات المتنقلة والثابتة. على الرغم من أن هذا الاستخدام الهائل ازدهرت به التنمية الاقتصادية إلا أنه تسبب أيضاً في مخاطر بيئية خطيرة. يستخدم محرك الديزل ظاهرة الاحتراق التي تولد NO_x ، SO_x ، جزيئات السناج والمركبات الخطرة الأخرى. تم تطوير تقنية إعادة تدوير غاز العادم (EGR) للتحكم في انبعاث NO_x أكاسيد النيتروجين. تقنية EGR اليوم ليست كما كانت عليه قبل بضعة عقود. تطورت مع مرور الوقت. إن دراسة التطور خلال العقدين ونصف العقد السابقين هي نطاق ورقة المراجعة هذه. كما تتم كذلك مناقشة العمل على تكنولوجيا التحكم والاستشعار ولكن النطاق الرئيسي لهذه الورقة هو مراجعة التطورات في تكنولوجيا EGR من منظور ميكانيكي. يوصف بإيجاز إضافة مكونات جديدة على طول الخط الزمني في التسلسل الزمني. يتم بذل جهد لقياس العمل في مجالات مختلفة وتوجيه العمل المستقبلي لتحسين تكنولوجيا EGR.

1. Introduction

Ever increasing energy demand and stringent regulation to control environmental pollutants like the emission of SO_x and NO_x are pressurizing the researchers to find energy viable and environmental friendly engine emission technologies [1]. Various techniques were applied to make IC engines especially Diesel engines energy efficient. One of these was the use of turbocharger that uses exhaust from the engine to drive turbine that in turn drives the air compressor to feed air at elevated temperature to the compression ignition engine [2]

In olden times smoke out of the chimney was considered the sign of prosperity of nation and then time changed and stringent laws was imposed to bring pollutants especially SO_x , NO_x and Lead (Pb) emission from engines to acceptable concentration in order to avoid their effects on human health, property, and aesthetics of the environment [3].

Scientists and engineers around the globe targeted to control NO_x emission from internal combustion engines. Exhaust gas recirculation technology was brought into play to control mainly the NO_x emission produced during the combustion of fuel. When Air enriched with oxygen react with Nitrogen at elevated temperature due combustion flame then NO_x are produced [4].

Exhaust Gas Recirculation (EGR) system diverts a part of the exhaust to the air inlet of diesel engine to make it diluted. It causes reduction in flame temperature due to reduction in availability of oxygen and an increase in heat capacity. It creates barrier in the reaction of nitrogen and oxygen to produce NO_x . Hence, EGR is also a tool to manipulate with combustion processes like Premixed Charge Compression Ignition (PCCI), Homogeneous Charge Compression Ignition (HCCI) and Low Temperature Combustion (LTC) [5–8].

Table 1: An overview of the effects of EGR on NO_x and pollutants emission [9–11]

No.	Effects	Reason of the effect	Consequences
1	Dilution of engine intake	<ul style="list-style-type: none"> Oxygen displacement from intake 	<ul style="list-style-type: none"> Reduced flame temperature.
2	Chemical effect	<ul style="list-style-type: none"> Dissociation of H_2O and CO_2 due to endothermic process 	<ul style="list-style-type: none"> Reduced power production.
3	Thermal effect	<ul style="list-style-type: none"> Heat capacity increase of the intake mixture 	<ul style="list-style-type: none"> Increased fuel consumption. Engine noise High soot production High HC and CO generation. High soot formation. Lube oil degradation Engine wear

Effects of Exhaust Gas Recirculation System are summarized in the Table 1. It explains that EGR technology causes dilution effect which in turn reduces flame temperature. Low flame temperature forces higher soot emission. The amount of air circulated by the Exhaust Gas Recirculation System is decided by the number of operating points set by the environmentalists to bring the emission below legislated limits.

Exhaust gas recirculation Technology was improved and evolved with passage of time to find a compromise between an acceptable NO_x emission and efficiency of the engine. Important modifications in EGR and their effectiveness will be discussed in the literature review section. Contribution of various authors is summarized in Table 2.

Novelty of this work is (a) to study evolution in EGR technology, (b) to compare the work of various authors regarding EGR, (c) various design modifications, and (d) Assessing the researches already done and suggesting future direction.

Table 2. Summary of contribution of various authors to study the impac of EGR on engine performance and emissions.

Contribution	Ref.
Agarwal et al. experimentally investigated the performance and emission for various EGR rates for direct injection diesel engines at constant speed. Hydrocarbons, NO _x , and carbon monoxide, smoke opacity and exaust gas temperatue were measured. High wear rate of piston rings and high carbon deposits were observed.	[12]
Millo et al studied various architectures of EGR system by experimental tests and 1D model. A combination of short an long route called Dual loop was evaluated. Dual loop was found to have 5% reduction in NO _x esmission.	[13]
Wei et al. studied the impact of EGR on gasoline engine and concluded that the technology can enhance fuel economy, reduces knocks and NO _x emission.	[3]
Asad et al. proposed a global equation to assess steady state and transient concentration in the exhaust.	[8]
Peng et al. investigated the impact of EGR on Direct Injection diesel engines during cold start. It was found that high EGR led to higher white smoke production. NO _x emission is affected by increment in fuel intake. EGR impact on NO _x reduction become significant when combustion become stable.	[14]
Hansen et al. investigated control architectures. Reference tracking and disturbance rejection are studied using model uncertainty.	[15]
Divekar et al. developed an EGR model for the quantification of interaction between oxygen intake and engine operating variable including EGR amount, intake boost, and fluel type.	[10]
Min et al. studied dual loop EGR with turbocharger for light duty diesel engines using sensors and product engines.	[16]

Jafarmadar and Nemati investigated the impact of EGR on exergy efficiency for diesel [17] engine operating with hydrogen and diesel oil.

Chen et al. assessed the impact of EGR on heavy duty diesel engine using diesel with [18] 40% butanol. It was concluded that EGR dramatically reduced NO_x emission with no effect on soot.

Galloni et al. studied the influence of EGR on turbocharged SI engine using both [19] numerical and experimental approach. The impact of EGR on octane requirement, engine performance, and exhaust gas temperature was studied for different rotational speeds.

2. Literature review

Diesel engine was considered low emission and environmentally promising technology until 1995 when United States Environmental Protection Agency (USEPA) put stringent policy and asked the state governments to enforce emission standards. Before that secondary emission control technology such as catalytic converter was not mandatory. It was difficult to fulfill the standards without secondary emission technology after USEPA's legislation [20].

Before that only catalytic activities are used to somehow control the NO_x emission. Use of ammonia was proposed as a reducing agent to control NO_x emission. Its usage on passenger's vehicle was hardly feasible [21]. It was suggested by certain laboratories to use CO and HC in the intake to control NO_x emission. This is how this technology came into play [20].



Exhaust Gas Recirculation (EGR) initially was a just conduit from exhaust channel to intake channel of the diesel engine [22]. EGR valve was integrated later in this conduit (Fig. 1). It reduced the oxygen nitrogen ratio in the intake and resulted in low combustion temperature and less availability of oxygen for the oxidation of Nitrogen contents of the intake in order to avoid NO_x emission. Unluckily the integration of EGR technology resulted in high emission of soot particles. Thus it was targeted by the researcher to reduce enhanced particulate concentration due to the integration of mentioned technology[23].

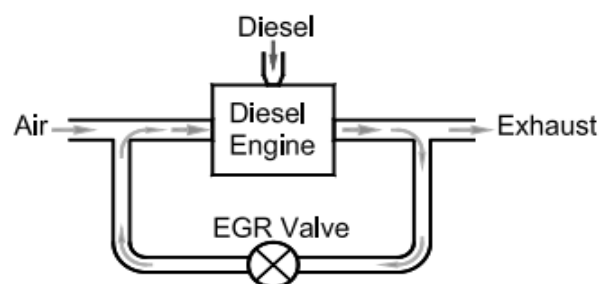


Fig.1. Exhaust Gas Recirculation (EGR) Conduit with EGR Valve.

Modeling and proportional integral derivative (PID) controller loop was investigated and control valves were integrated in the conduit that allows some of the combustion product into the intake tract of the engine. The problem in the use of this technology was that variation in pressure and EGR rate were dependent on the both variables named Turbine vane Position and Value Position (degree of openness or closeness). Problem was solved by activating only one loop while keeping other variable constant. PID controller was proved more effective than Model Predictive Control (MPC) [22]. PID was designed to change set point on the change of variables and it ultimately caused strong EGR Rate Change for optimum value. In this way the EGR was made better and effective to control the composition of the mass that was to be charged to diesel engine[24].

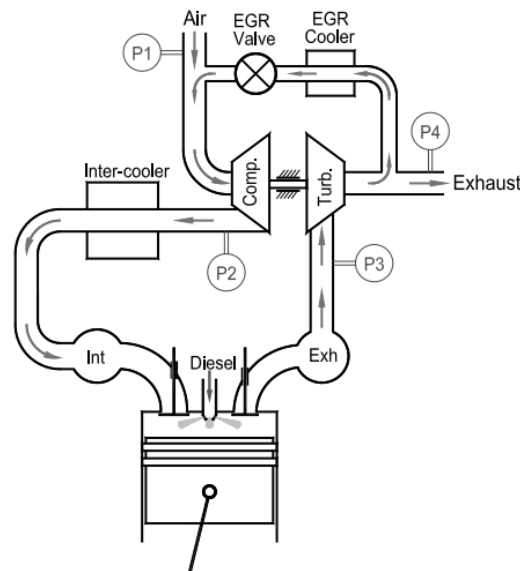


Fig. 2. Integration of Exhaust Gas Recirculation (EGR) Cooler.

The EGR technology was improved when new generation of control valves came in and accuracy was improved by electronic systems. Further, EGR cooler was used for more reduction in NO_x emission than the conventional one. Therefore Exhaust Gas Recirculation Cooler (EGR) was also integrated in to the EGR system to get the emission controlled (Fig. 2). G.H. Abd-Alla [25] used Ricardo E6 Engine and installed an EGR system. Temperature of exhaust gas was noted by inserting thermocouple in the EGR pipe near the intake manifold. Part of the EGR pipe was manufactured by using flexible stainless steel. Flexible Stainless steel was used to absorb engine vibrations those can destroy exhaust system and measuring instruments. Pipe of EGR was insulated by using Glass wool. It helps to reduce temperature drop. The schematic is shown in the Fig. 3.

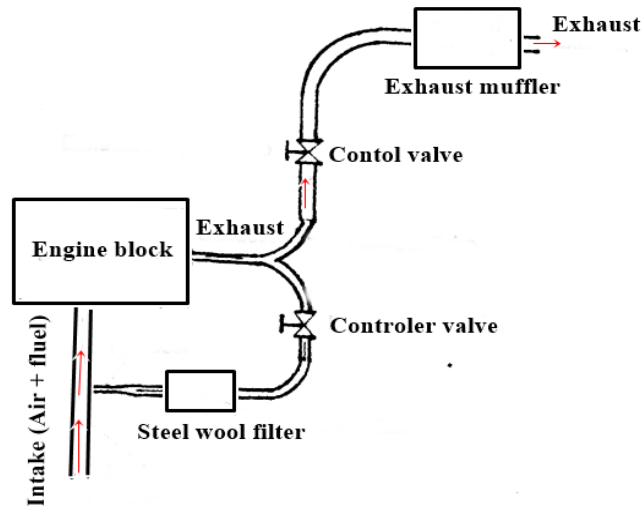


Fig.3. Exhaust Gas Recirculation (EGR) system with flexible steel pipe design for vibration control.

Inlet air was removed and equal volume of combustion products were inserted into the air intake channel. That resulted in 14% reduction in flow rate due to EGR. Some of the air is displaced by water vapors and CO_2 which are integral parts of combustion products. The application of EGR reduced N_2 flow rate by 15% and O_2 by 19%. Dilution of intake mass with exhaust increased the mass temperature that significantly affected combustion process. The effect of reduction of O_2 concentration by dilution of CO_2 , N_2 and exhaust gas was traced as shown in Fig. 4 [25].

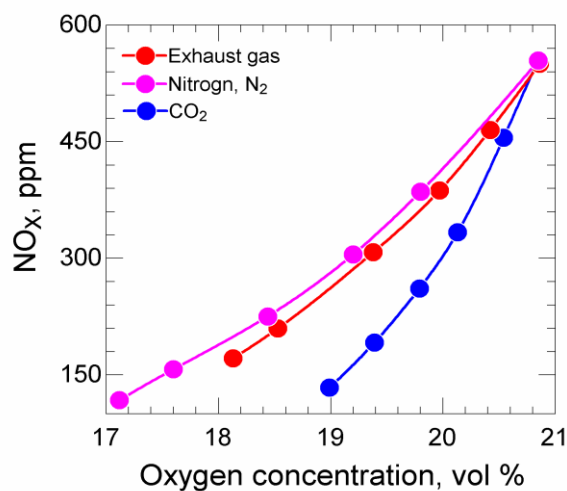


Fig.4. Effect of reduction in oxygen concentration by different diluents (EGR, CO_2 , N_2) on NO_x emissions in diesel engine.

It was also found that the use of EGR system had several draw backs as well. Use of EGR increased specific fuel consumption and particulate emission especially at high loads. It has an adverse effect on lubricating oil quality and engine durability. The emission of CO_2 was enhanced due to this technology. However NO_x emission was reduced with the combined use of superchargers and EGR System [25].

Initially control valves along with PID were used to enhance the performance of EGR system. PID was designed to change set point on the change of variables and it ultimately caused strong EGR Rate Change for optimum value. Latter design was modified and EGR cooler was introduced along the EGR duct [26]. M. Zheng et al. [22] proposed to use a Catalytic Oxidation Box to maintain a safety margin of ash contents in 2004 (Fig. 5). It was proposed that it could make EGR more stable during inconsistencies of the operation of EGR [8].

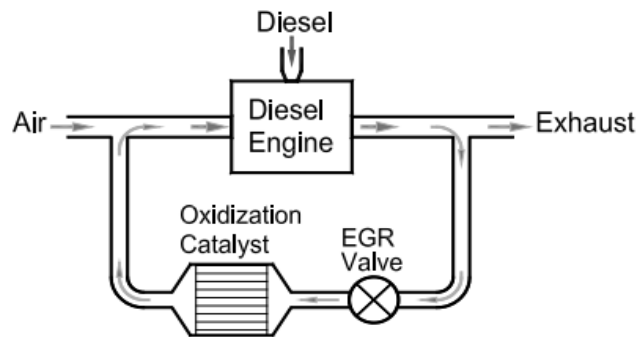


Fig.5. Catalytic Oxidation Box integration in Exhaust Gas Recirculation System.

M. Zheng et al. [22] proposed the use of EGR Reformer in the same study (Fig. 6). Reformer can be used to produce carbon mono-oxide and hydrogen so they might facilitate premixed combustion enhancement in the cylinder [22].

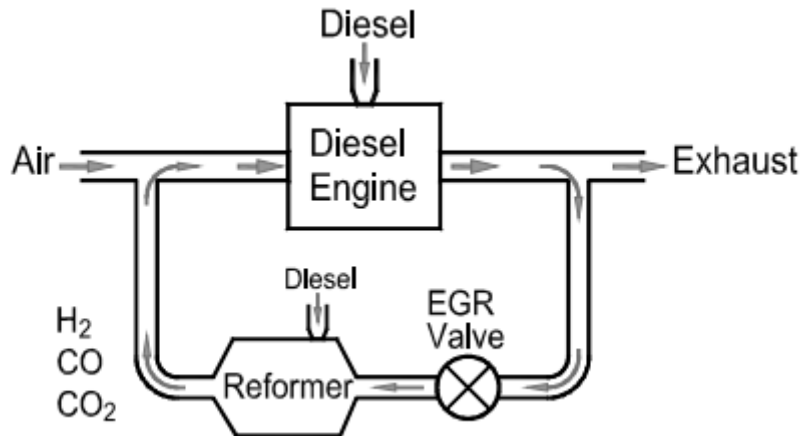


Fig.6. Integration of Reformer in Exhaust Gas Recirculation (EGR) System.

R. Moss et al. [27] tried to put sensor technology in order to measure EGR rate. Position sensor was used to determine the degree of opening of the throttle valve enabling EGR control loop. EGR control rate depends on temperature, pressure difference, intake and exhaust restrictions or exhaust gas recirculation fouling. To compensate these environmental factors direct measurement of EGR rate is mandatory. He used temperature sensor, mass flow meter and back pressure sensor to get the direct measurement of EGR as shown in the Fig. 7.

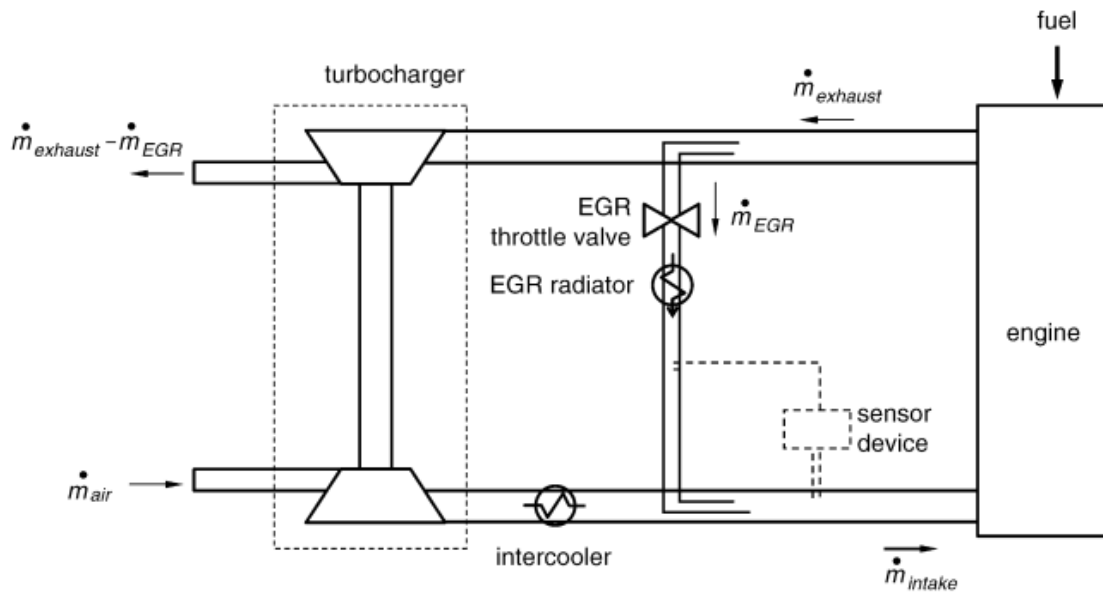


Fig. 7. Layout to put sensors in order to directly measure EGR rate.

Integration of Air Box was reported by Agarwal et al. [12] in his work in 2009. The flow of exhaust fluctuates when the exhaust is allowed to pass through Exhaust Gas Recirculation (EGR) channels. It happens due to the large pressure difference of intake air in the intake manifold and exhaust manifold. Exhaust pressure is higher due to higher temperature of exhaust as compared to fresh air. This difference in pressure caused fluctuations and turbulence in the flow of exhaust in the EGR loop. The problem was taken in to account by Agarwal et al by introducing Air Box in the EGR loop having a diaphragm as shown in the Fig. 8 below [12].

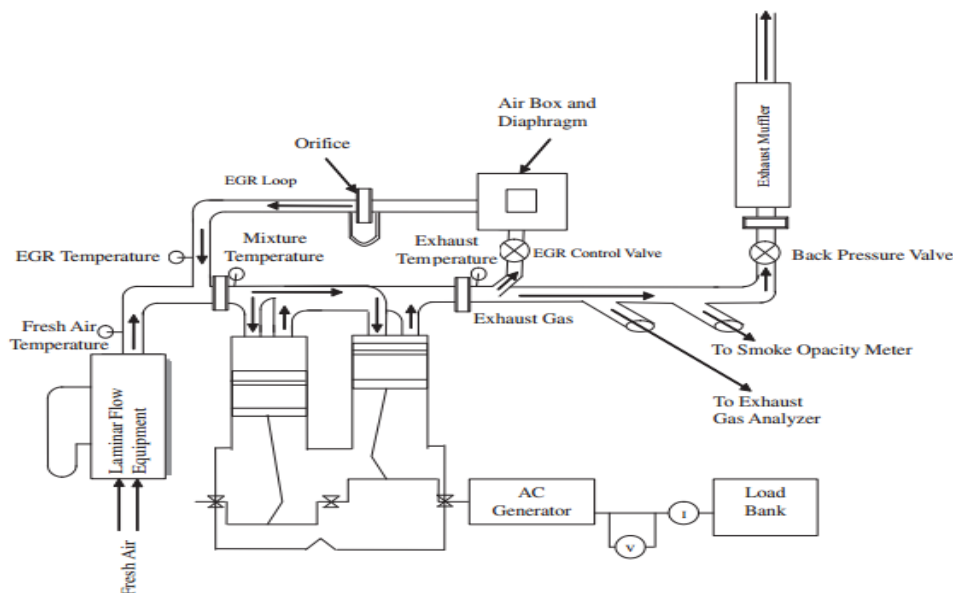


Fig.8. Air Box Technology in the Exhaust Gas Recirculation (EGR) Loop.

They used an orifice to measure flow rate and EGR temperature sensors to monitor temperature of exhaust that need to be mixed with fresh incoming air.

High Pressure or Short Route (SR) Layout and Low Pressure or Long Route (LR) Layout was discussed by F. Millo et al. [28] in 2012. They also used Diesel Particulate Filter (DPF) to capture particulate matters from the exhaust. It saves compressor damage from particulate matters as well. Both Short Route (SR) and Long Route (LR) architecture can be combined to get a mixed one or Hybrid Layout. But in that case it must have a bypass system as extremely cooled EGR can increase unburned hydrocarbons and carbon mono-oxide emission especially during start up due to combustion instability. Although, SR is preferred for vehicles but LR layout of EGR is more environmentally friendly due to integration of DPF. Both system of layout of EGR are shown in the Fig. 9 [9].

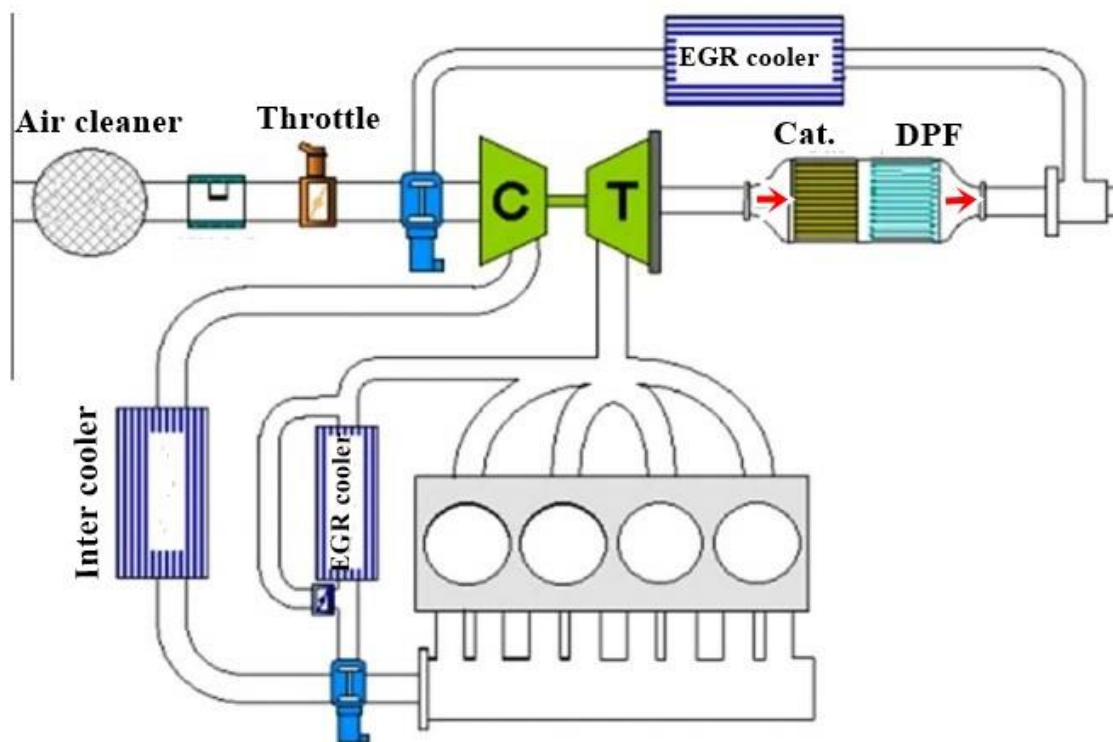


Fig.9. Short Route (SR) and Long Route (LR) Exhaust Gas Recirculation Layouts.

DPF reduces the damage to compressor wheel and charge air cooler fouling. It has the capability to hinder carbonaceous contents from the exhaust. Therefore it saves not only compressor wheel damage but also stops accumulation of these matters in the intercooler channels. Diesel Particulate Filter (DPF) also produces necessary plumbing effect in exhaust gas recirculation circuit that in turn offers optimum resistance to the flow of exhaust [28].

DPF is also called Diesel Particulate Trap (DPT). It uses different types of technology like honey comb aluminum mesh, aluminum wire mesh, and ceramic fiber technology. Honey comb mesh is the most recent technology. Regeneration process was designed to clean the filter from particulate matters. Active and passive regeneration processes are used to convert particulate matters into CO_2 without causing a damage to filter. Temperature is build up to 500°C upon receiving a signal from particulate stack monitoring system to burn the particulate matters in the active regeneration. But now a day a passive or catalytic regeneration is preferred due to

economic limitations. Catalytic oxidation is used in the passive technique to achieve the same purpose as shown in Fig. 10 [29].

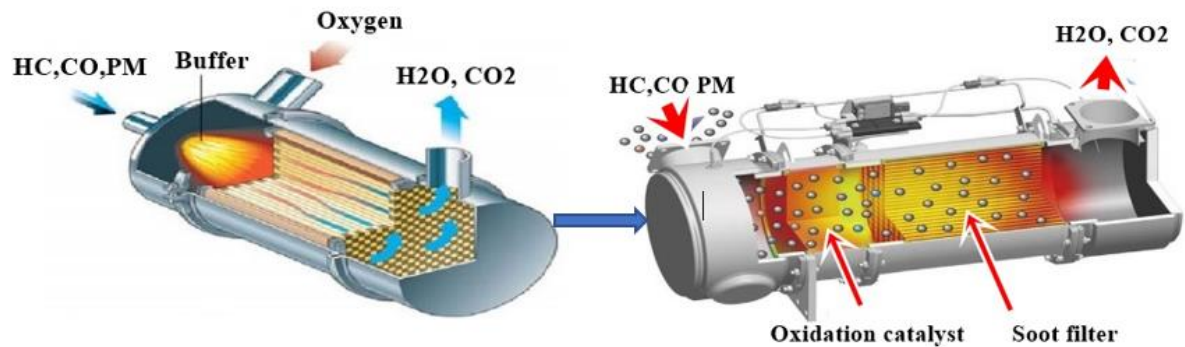


Fig.10. Advancement in Regeneration Process from Active to Passive Regeneration in DPF

F. Millo et al. [28] also studied the soot and NO_x emission for both Short and Long Route EGR systems. Schematic diagrams for both long and short route exhaust gas recirculation system are shown in Fig. 11.

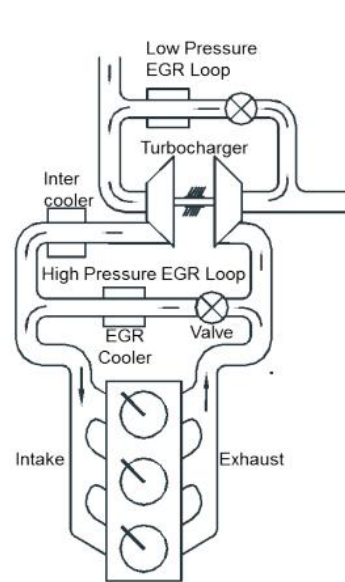


Fig.11. High Pressure and Low Pressure EGR loops in modern engines.

Mostly diesel engines in this age use High Pressure (HP) EGR while others rely on Low Pressure (LP) EGR. High Pressure EGR is prominent technology for production engines while low to moderate pressure EGR systems are used in common application. Both HP and LP EGR systems used in modern diesel engines. Their comparison with respect to soot emission is summarized in Fig. 12. Exhaust is allowed to pass first through compressor due to which it loses its temperature energy. Reduction in temperature causes reduction in pressure as well [10].

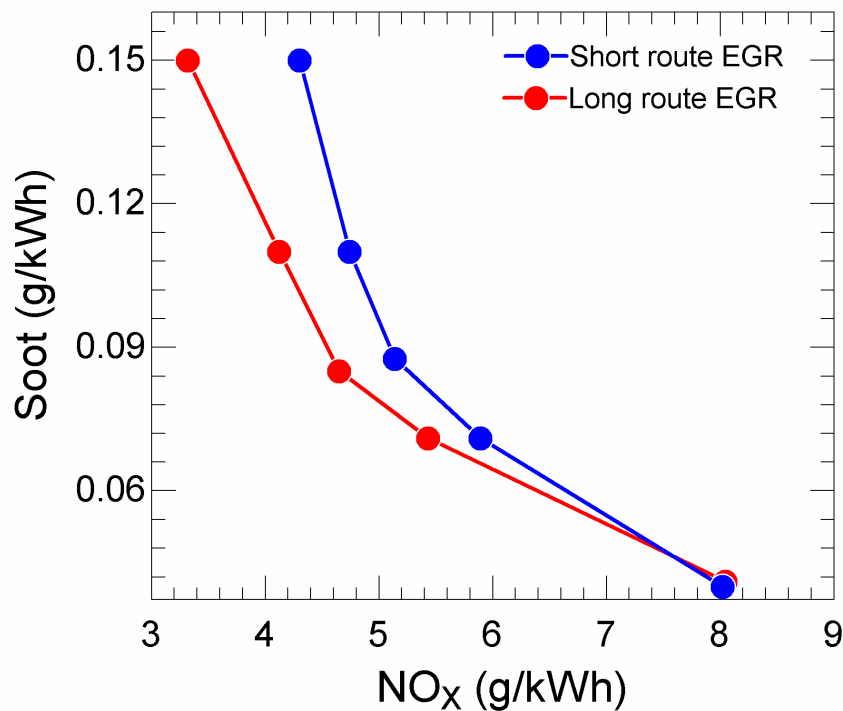


Fig.12. Soot and NO_x emission as a function of EGR rate for both short and long route EGR.

Exhaust Gas Recirculation (EGR) cooler was used by many researcher before its injection into the intake manifold of the engine. Combustion residue including soot particles, unburned hydrocarbons and their mixture is allowed to pass through the EGR cooler. Soot particles and unburned hydrocarbon deposits an insulating layer that causes a significant reduction in the thermal efficiency of EGR cooler [30]. Beside reduction in thermal efficiency, it affects intake pressure, and engine efficiency. In order to minimize these losses Janabi and Malayeri [31] investigated different design modifications in the EGR cooler. They experimentally investigated the effects of grooved plates, straight and inclined ribbed plates as shown in Fig. 13. They concluded that although ribs developed a flow separation and turbulence but have better overall thermal efficiency. Flat ribbed are particularly suitable in term of low thermal resistance as compared to other structural designs. Groove plates performance depends on the dimension of grooves that need to be investigated yet.

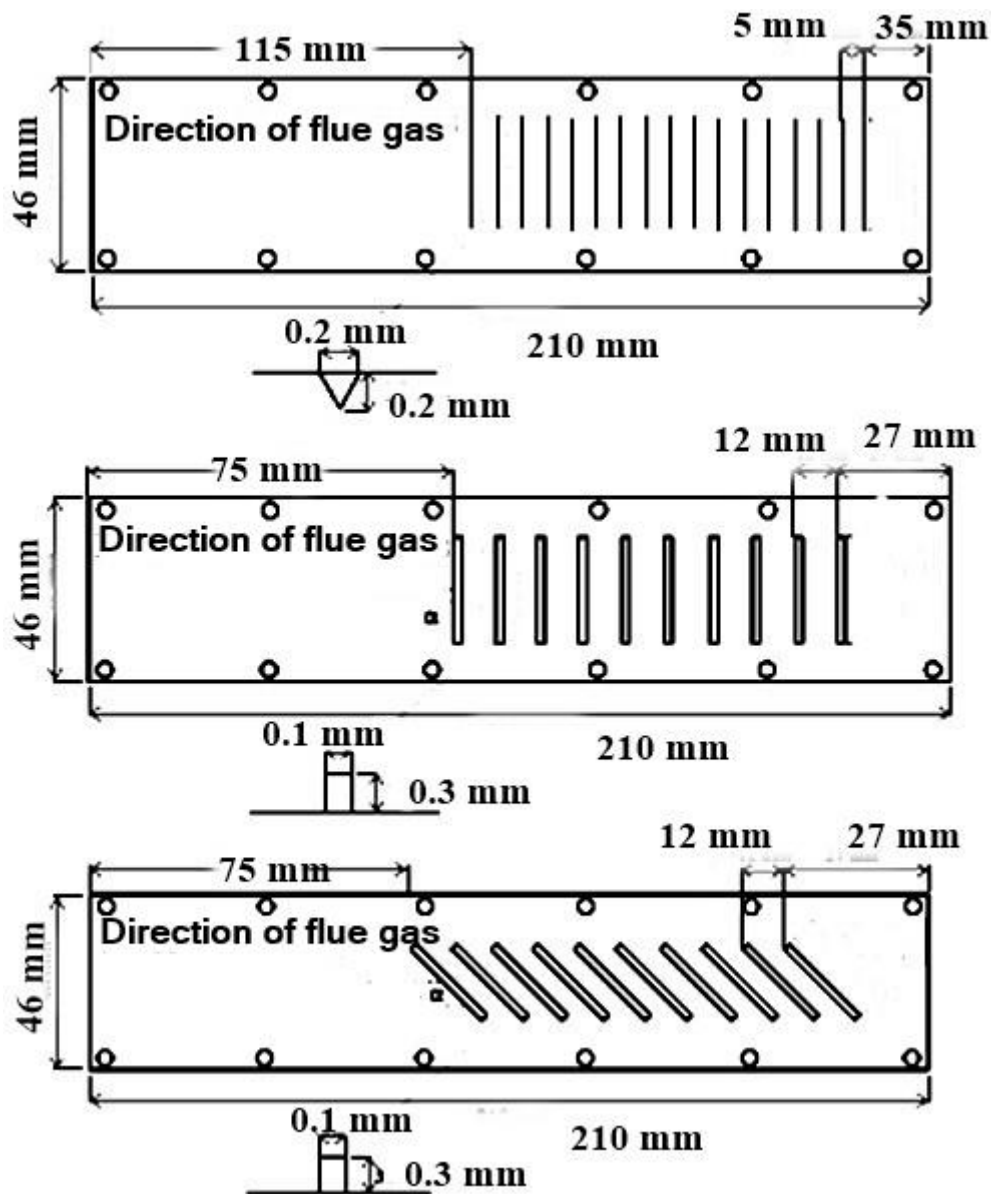
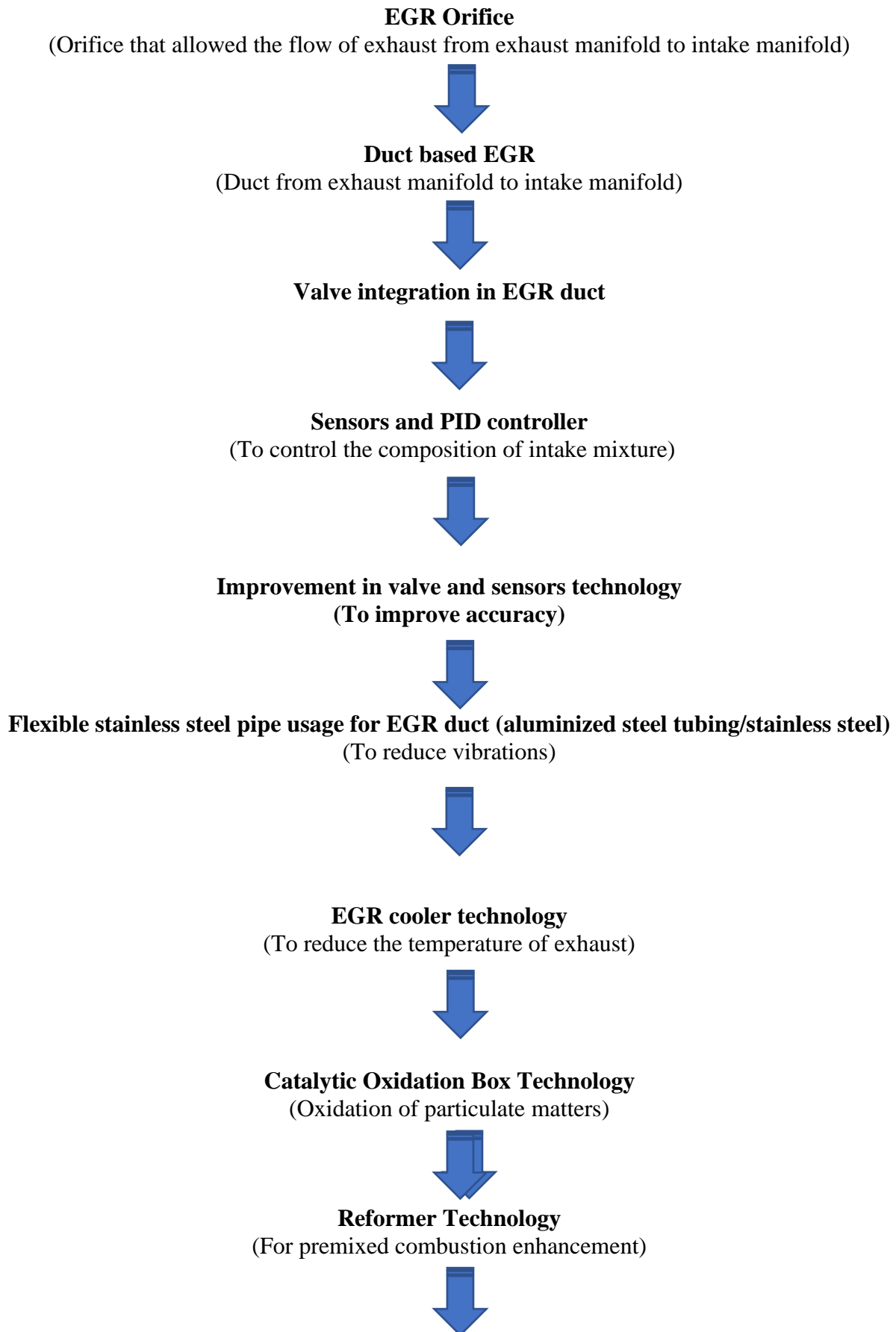


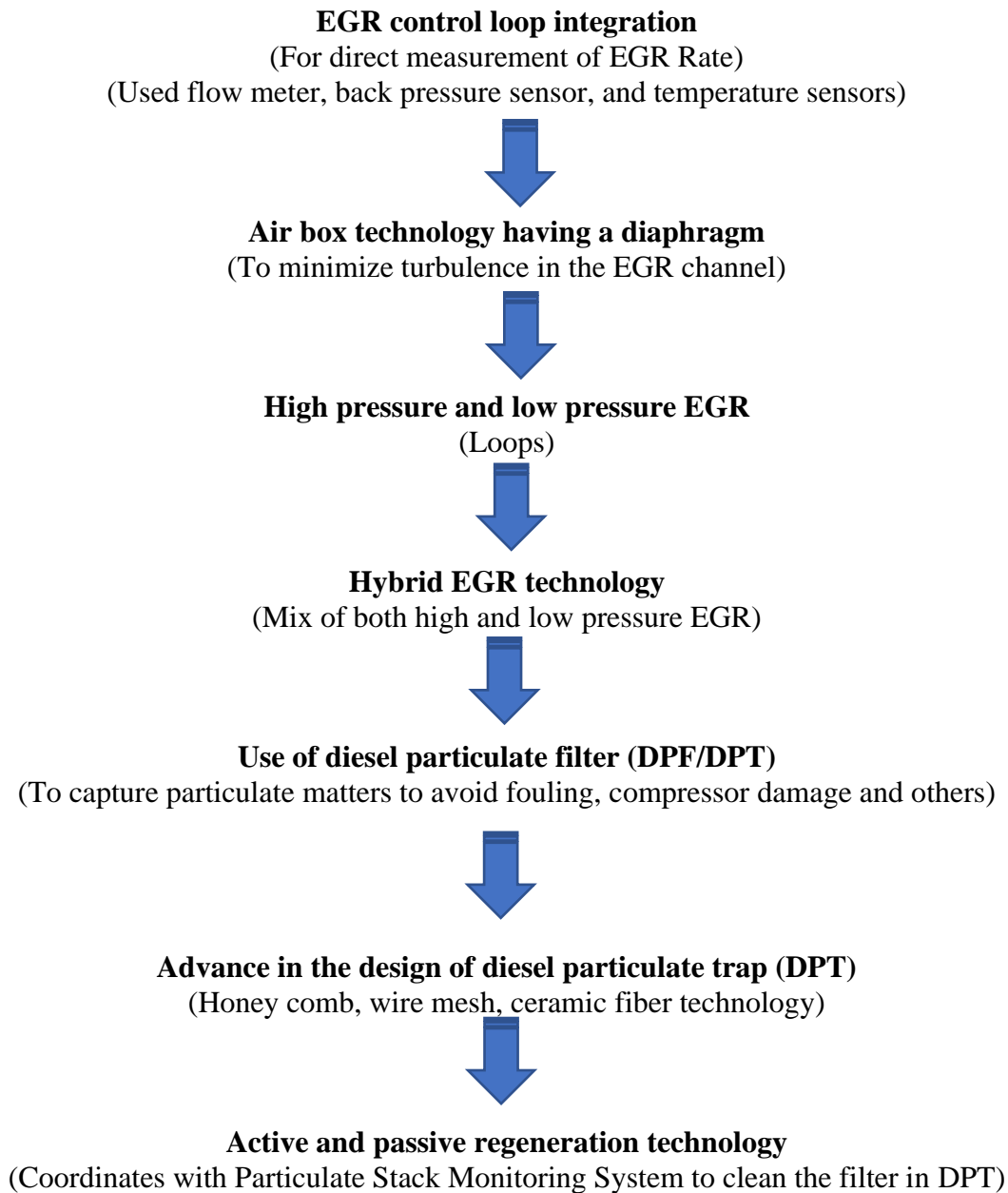
Fig.13. Design of grooved plates, straight ribbed plates, and inclined ribbed plates in the EGR cooler.

3. Summary

Exhaust Gas Recirculation (EGR) was no more than an orifice that allowed the exhaust of the engine from exhaust manifold to the intake manifold. Pressure difference was the driving force to push the exhaust from exhaust to the intake mixture. The technology evolved with the passage of time. Evolution in EGR technology with time is shown in the form of flow diagram below.

EGR evolution Tree





3.1. Critical analysis and future work recommendations

EGR diverts a part of exhaust to reduce the concentration of oxygen. It is done to control the NO_x emission as limited oxygen deprive of nitrogen to oxidize. It also reduces flame temperature for combustion.

Although EGR is promising technology to reduce NO_x emission but it deteriorates engine efficiency as well. Researcher tried to find a compromise between the two. Therefore, it is desired to improve the effectiveness of EGR with minimum impact on engine efficiency. Although a lot of work was done to improve control technology to make EGR more effective but major concern of this paper is to critically review mechanical advances in EGR technology.

Beside Efficiency reduction another problem caused by the EGR technology is soot emission enhancement (Fig.14). Soot is the major source of fine suspended particle that are carcinogenic for human health. They enter human body through respiratory systems and cause damage to brain cells as reported by B. Rajesh Kumar et al. [32].

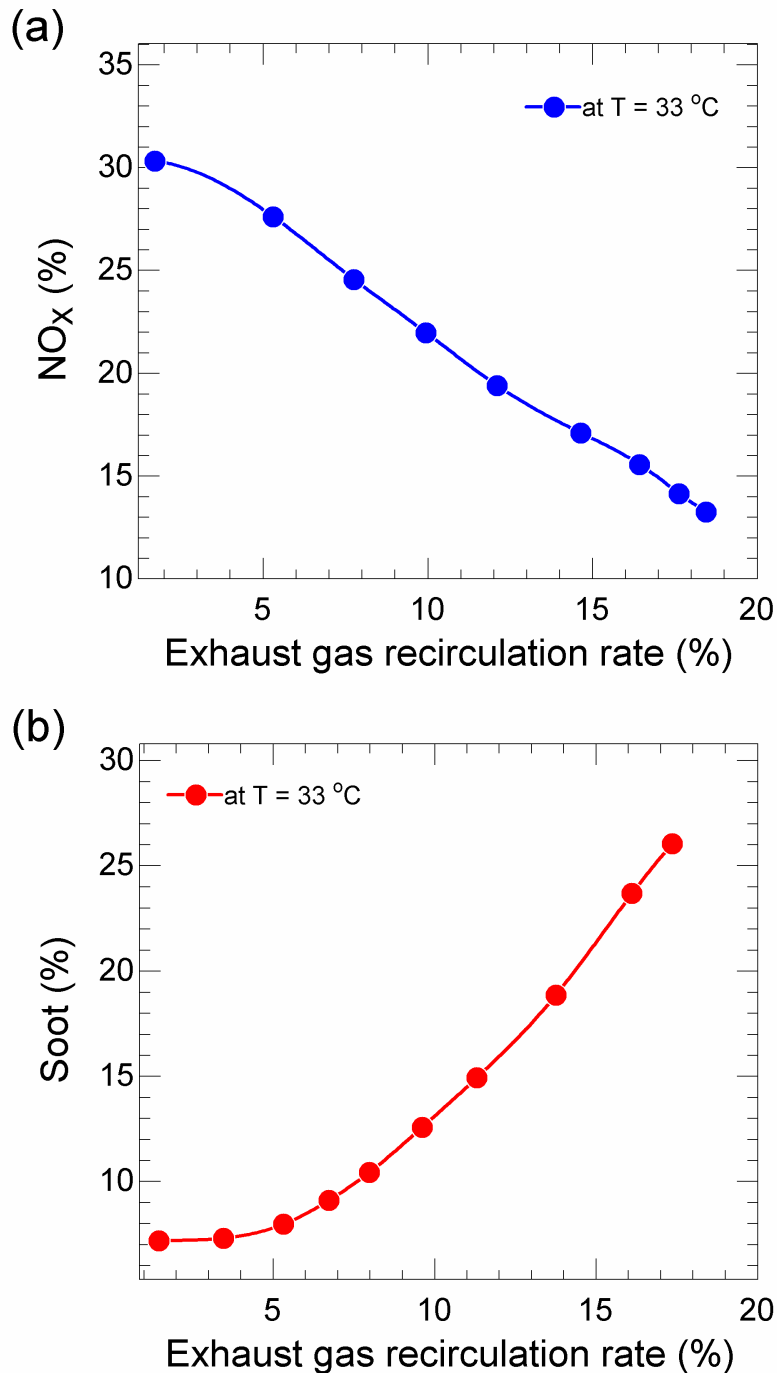


Fig.14. (a) Decreasing NO_x and (b) increasing soot emission with increasing EGR Rate [33].

Therefore, we must look for alternate fuels like biofuels as they are comparatively better option regarding energy security concerns. Efforts should be made to maximize the

utilization of other energy sources like electricity. Best advancement is hybrid cars technology that can be operated at electricity beside fossil fuels.

G.H. Abd-Alla [25] used flexible steel pipe for Exhaust Gas Recirculation System so that vibration may be controlled as vibration might be disastrous for the instruments. More research can be done in this area to find the most effective way of vibration control.

Similarly Agarwal et al. [12] reported the use of air box to control turbulence phenomenon inside EGR system. Turbulence in EGR was not studied in detail. Research is needed to study the flow of exhaust in different geometries of EGR to minimize turbulence effect.

F. Millo et al. [28] used Diesel Particulate Filter (DPF/DPT) to trap matter particulates. It is very useful technology as it will hinder most dangerous carcinogenic particles to enter in the atmosphere. But efficiency of DPF deteriorates due to blockage of wire frame like structures. It means it is to be cleaned out repetitively for good performance. Researcher needs to concentrate to improve DPF such that it does not require regular cleaning. Same is the case with fouling effect in the intercooler and EGR cooler.

Janabi and Malayeri [31] took an initiative to investigate change in the design of EGR cooler. They studied the effect of grooved plates, straight and inclined ribbed plates and preferred to use flat ribbed plates. But they have not investigated fluid dynamics of exhaust passing through holes of grooved plates and have not optimized grooved size according to flow requirement.

Similarly, ribs geometry, number of ribs, and ribs angle with the flow are all need to be investigated in detail to optimize the exhaust flow in EGR cooler with minimal thermal resistance.

4. Conclusion

This paper summarizes the evolution in the design modification in Exhaust Gas Recirculation (EGR) technology in chronological order. EGR is a technology that pushes a portion of exhaust from exhaust manifold into the intake manifold of diesel engine. This reduces oxygen availability for nitrogen to oxide and hence create barrier for production of NO_x during combustion process.

EGR causes reduction in flame temperature. Reduction in flame temperature reduces power production by IC engine. Benefits and side effects of EGR technology are discussed and various improvement in public literature are assessed. A lot of work has been done in previous few decades but more work needs to be done in certain area like DPT cleaning, intercooler design and air box design optimization to minimize turbulence in the channels of EGR. It is also proposed to carry out research to modify the geometry of EGR, may be through CFD analysis, to minimize resistance and turbulence. Following can be established in the current review:

1. Increase in oxygen concentration in the intake of IC engine results in increase in exhaust gas, nitrogen and carbondioxide emission.

2. Soot emission is reported to have increasing trend with decrease in NO_x emission.
3. Soot emission is comparatively lower for long route exhaust gas recirculations system.
4. NO_x emission decreases with increase EGR rate.
5. Soot formation increases with increase in EGR rate.
6. Flame temperature is reduced due to EGR technology.
7. Power produced by IC is reduced by the use of EGR technology.
8. Use of intercooler and EGR cooler reported to increase the effectiveness of EGR technology.

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Appendix

Comp.	compressor
Cat.	Catalytic converter
C	compressor
DPF	Diesel Particulate Filter
DPT	Diesel Particulate Trap
EGR	Exhaust Gas Recirculation
HP	High Pressure
HCCI	Homogeneous Charge Compression Ignition
IC	Internal Combustion
LR	Long Route
LP	Low Pressure
LTC	Low Temperature Combustion
NO _x	Oxides of Nitrogen (NO and NO ₂ etc.)
PID	Proportional Integral Derivative
PCCI	Premixed Charge Compression Ignition
SR	Short Route
SO _x	Oxides of Sulphur
Turb.	turbine
USEPA	United States Environmental Protection Agency

Environmental Impacts of Phosphate Rocks on the Water Quality of Rivers

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Abstract: One of the important natural sediment rocks impacting aquatic environment is Phosphate Rocks (PR). PR comprises from several chemical compositions such as heavy metals. Mining and transportation of PR nearby or through the rivers may expose them to pollution. Some elements such as salts and heavy metals may be leached out into the water, when PR is in contact with water due to dipping in water streams, precipitation events, or changes in water table. In this study via experimental lab work, PR leachability was investigated when it immersed in Nile River. The research work focused on evaluating the release of some constituents, including phosphors, cadmium, chromium and lead of PR on the water quality of Nile by using leaching experiments. In these experiments, the potential impact of changing conditions, such as liquid to solid ratio (L/S) and phosphate content in PR on long-term leaching of phosphor and heavy metals. Results revealed that phosphors and lead were released in high concentrations, while cadmium and chromium leached out in very low concentrations. PR leachate out 32 mg/L of phosphorus into Nile water, which it is too much more than the allowable values for natural streams, i.e. 0.5 mg/L. Therefore, if phosphate rocks are submersed intentionally or unintentionally into Nile river water, this will lead to environmental risks in the area of PR submersion.

Keywords: Phosphate Rocks, leaching tests, Water quality, Nile River

الخلاصة: تعتبر صخور الفوسفات (PR) من أهم صخور الرواسب الطبيعية التي تؤثر على البيئة المائية. يتكون PR من عدة تركيبات كيميائية مثل المعادن الثقيلة. تعدين ونقل PR القريبة من الأنهار أو عبرها قد يعرضها للتلوث. يمكن تسرب بعض العناصر مثل الأملاح والمعادن الثقيلة في الماء، عندما يكون PR على اتصال بالمياه بسبب الغمر في مجاري المياه، أو أحداث الترسيب، أو التغيرات في منسوب المياه الجوفية. في هذه الدراسة عبر العمل المختبري التجريبي، تم التحقق من قابلية العلاقات العامة للانغماس عند غمرها في نهر النيل. تركز البحث على تقييم إطلاق بعض المكونات بما في ذلك الفوسفور والكاديوم والكروم والرصاص في PR على جودة مياه النيل باستخدام تجارب الرش. في هذه التجارب، التأثير المحتمل للظروف المتغيرة، مثل نسبة السوائل إلى الصلبة (L / S) ومحتوى الفوسفات في PR على ارتشاح الفوسفور والمعادن الثقيلة على المدى الطويل. أوضحت النتائج أن الفوسفور والرصاص تم إطلاقهما بتركيزات عالية، بينما تسرب الكاديوم والكروم بتركيزات منخفضة للغاية. مادة PR تسرب 32 ملغم / لتر من الفوسفور إلى مياه النيل، وهو أكثر بكثير من القيم المسموح بها للمجاري المائية الطبيعية، أي 0.5 ملغم / لتر. لذلك، إذا تم غمر صخور الفوسفات عن قصد أو عن غير قصد في مياه نهر النيل، سيؤدي ذلك إلى مخاطر بيئية في منطقة غمر PR.

1. Introduction

The raw material to produce phosphate fertilizers and other chemicals is Phosphate Rocks (PR), thus there is a high demand worldwide for these materials [1]. However, these rocks comprise of many chemical compounds and dangerous constitutions. PR usually contains heavy metals such as uranium, cadmium and zinc with high contents more than other natural stones, for example, limestone and sandstone [2; 3]. PR contains three types of hazardous elements, which can be recognized as heavy metals, radiation elements and rare earth elements. The first two types are the most alarmed environmental pollutants. The chemical composition of the PR varies from place to the other over the world. For instance, it is reported that in Egypt lead, gold, cadmium, mercury, and uranium in phosphate rock are 4.0, N/A, 2.3, 0.05, and 27.0 mg/kg respectively [4]. While these elements are higher in some places such as in Morocco as PR contains 7.0, 13.0, 3.0, 0.04, and 82.0 mg/kg respectively [5].

PR is considered as a mixed mineral system because it is rich in a calcium carbonate and calcium magnesium carbonate. Some elements such as salts and heavy metals may be leached out into the water, when PR is in contact with water due to dipping in water streams, precipitation events, or changes in water table. Leaching tests are the common tools for evaluating the effect of water contact with solid materials. Four types of leaching tests can be

adopted for inorganic pollutants, namely column and tank tests, availability and static-pH [6]. Main effective conditions in leaching tests are pH, liquid to solid (L/S) ratio and contact time. For PR leachability, Jiang, et al. [7] tested different types of PR wastes in different pH environments. The results revealed that the acidic condition could affect phosphorus leaching more considerably than neutral and basic conditions. The phosphorus leached out under acidic environments was much greater than that under neutral or basic ones. Thorneloe et al. [8] reported that the constituent of potential concern concentration at approximately pH equal 2 can be used as an indicator to estimate the total content of the phosphorus in a PR. Therefore, the content of the phosphorus in the solid stage of different PR could be assessed as 1.39 to 1.62 g/kg. Garrabrants et al. [9] recommended that 5 mL/g of the L/S ratio is the most suitable ratio for leaching behaviors of PR in both short-period and long-period. Jiang, et al., [7] concluded that phosphorus release of the PR in the liquid stage declined with L/S ratio increase.

The main leachability constituents from PR are some heavy metals and phosphorous. Heavy metals, in general, cause serious effects on the health of human being. Cadmium, lead and chromium are the most heavy metals encountered in PR, which they result in growth of autoimmunity disease, which makes immune system of the person to attacks its own cells and cause irreversible brain damage. While, increase pure white phosphorus in environmental surroundings can be a severe hazard to human health. White phosphorus is enormously toxic and exposure to it lead to death. Many dangerous diseases such as kidney damage and osteoporosis can be occurred due to exposing to much phosphate. On the other hand, phosphorus are nutrients for natural parts of aquatic ecosystems. Increase phosphorus with nitrogen from atmosphere supports the bloom growth of algae and aquatic plants, resulting in serious environmental and human health issues, and affecting the economy as well [10].

In this study, the release characteristics of PR submersed in a river water such as Nile River was examined by a tentative lab program. The research work aims to assesses advise influence of some components such as phosphors, chromium, lead and cadmium, of PR on the Nile water quality by employing leaching experiments. These experiments investigated parameter effects such as liquid to solid ratio (L/S) and phosphate content in PR on long-term release of heavy metals and salts into the Nile water. The relatively high L/S ratios were chosen to simulate the Nile water amount in comparison to the immersed solid martial of PR into Nile.

2. Methods

PR used in this experimental work was brought from El Sbeaea region in Aswan governorate, Egypt. PR samples was screened and grinded with size of around 5 mm. Material colour is off-white to light brown. PR samples contains 24, 28 and 30% of P_2O_5 . Figure 1 shows size and shape of PR materials. Leaching experiments include sinking PR samples in distilled water and Nile waters at different three L/S ratios, namely 50, 100 and 200 L/kg. Materials and test procedure are shown in Figure 1. Six test containers were used. Four of them had 24% of P_2O_5 with three different L/S ratios from distilled water and one with natural Nile water. The fifth

and sixth container had a 28 and 30% of P_2O_5 respectively with distilled water. Experimental programme details are presented in Table 1.



Figure 1. Phosphate rock material and leaching tank test procedure

Water samples of 100 ml were collected from the test containers at different intervals namely, 1, 7, 14 and 64 days. Then the same amount of distilled water was added to keep L/S ratios fixed. One sample was collected initially from pure Nile water without PR. All water samples were chemically analysed to determine the phosphor, lead, chromium and cadmium concentrations by using Inductivity Coupled Plasma Mass Spectrometry (ICP-MS).

Table 1: Experimental programme Details

Sample no.	Water type	P_2O_5 (%) in PR	L/S (weight)	Collection time (days)
S0	Nile (N.W)	---	---	0
S1	Nile (N.W)	24	200/1	1,7,14, 64
S2	Distilled (D.W)	24	200/1	1,7,14, 64
S3	Distilled (D.W)	24	100/1	1,7,14, 64

S4	Distilled (D.W)	24	50/1	1,7,14, 64
S5	Distilled (D.W)	28	50/1	1,7,14, 64
S6	Distilled (D.W)	30	50/1	1,7,14, 64

3. Results

Phosphorus leachability was presented as liquid phase concentration (mg/L). All results are average of three readings with a standard deviation, for example, for phosphor and lead concentrations as ± 5.6 and 0.048 mg/l respectively. The experimental results were discussed in the following sections.

3.1 Electrical conductivity (EC)

Electrical conductivity, EC, of acquis systems measures their ability to conduct an electric current and accordingly it increases with the increase in the amount of dissolved ions into water. Experimental results, herein, showed that there is a great increase in EC accompanying PR 24% submersion in the Nile water with time in comparison to the control case, as shown in Figure 2. This indicates to release PR a lot of ions into water and this release continued with time. The figure shows also that the ability of PR leaching is higher in Nile water than distilled water. This is perhaps because the Nile water composition has chemical contents which eager the releasing properties of PR. In addition, results confirmed that increase L/S ratio led to decrease the release of the PR contents into water. In addition, the increase of P_2O_5 in PR increases the release of PR. In fact, there are other chemical compositions of PR controlling leaching properties with P_2O_5 . It is reported that beside P_2O_5 in PR, CaO and SiO_2 are the main contents and there are some minors of other chemical compounds such as CO_3 , Na and Mg. [11]

3.2 Total dissolved solids (TDS)

Figure 3 presents the experimental measurements of TDS values. Results showed a well agreement with the previous results of ECs. Dissolved solids increased with increase in the contact time between PR and water. Nile water contents of the dissolved solids are almost doubled due to PR leachate. TDS values increased with decrease in the L/S ratio. P_2O_5 ratio of PRs had also the same results as EC results.

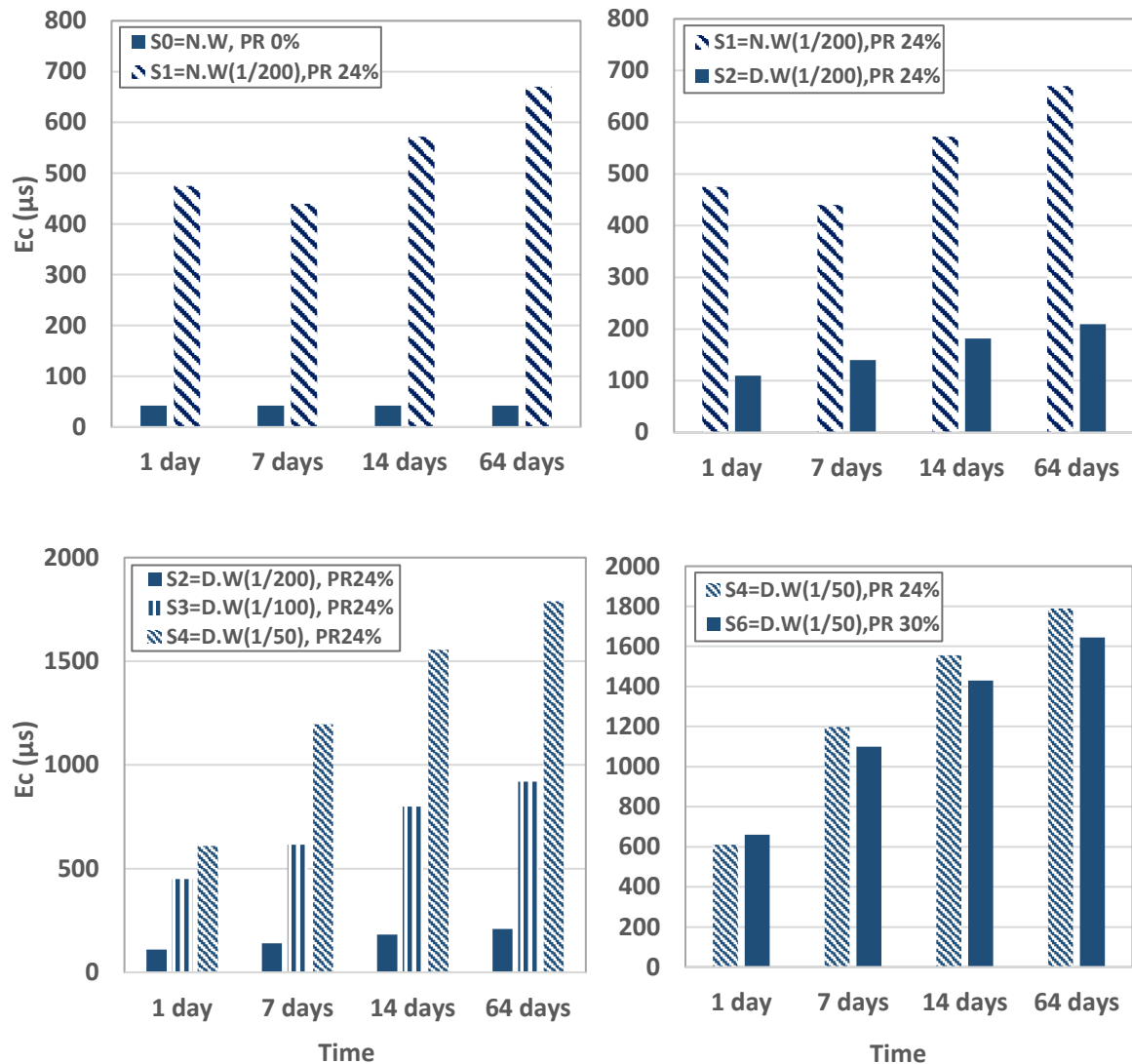


Figure 2. Electrical conductivity readings with time

3.3 Phosphor release

Figure 4 presents the phosphor release concentrations under different conditions. Phosphor results showed that after one day the content of phosphor folded more than ten times of the initial concentration found in the Nile water and the concentrations increased greatly with time. Results showed that there is a small change due to increase L/S ratio in phosphor concentrations and in case of using distilled water as well. The figure shows also that 30% P_2O_5 ratio of PR exposed a high level of phosphor release while 24 and 28% were smaller and having closer values.

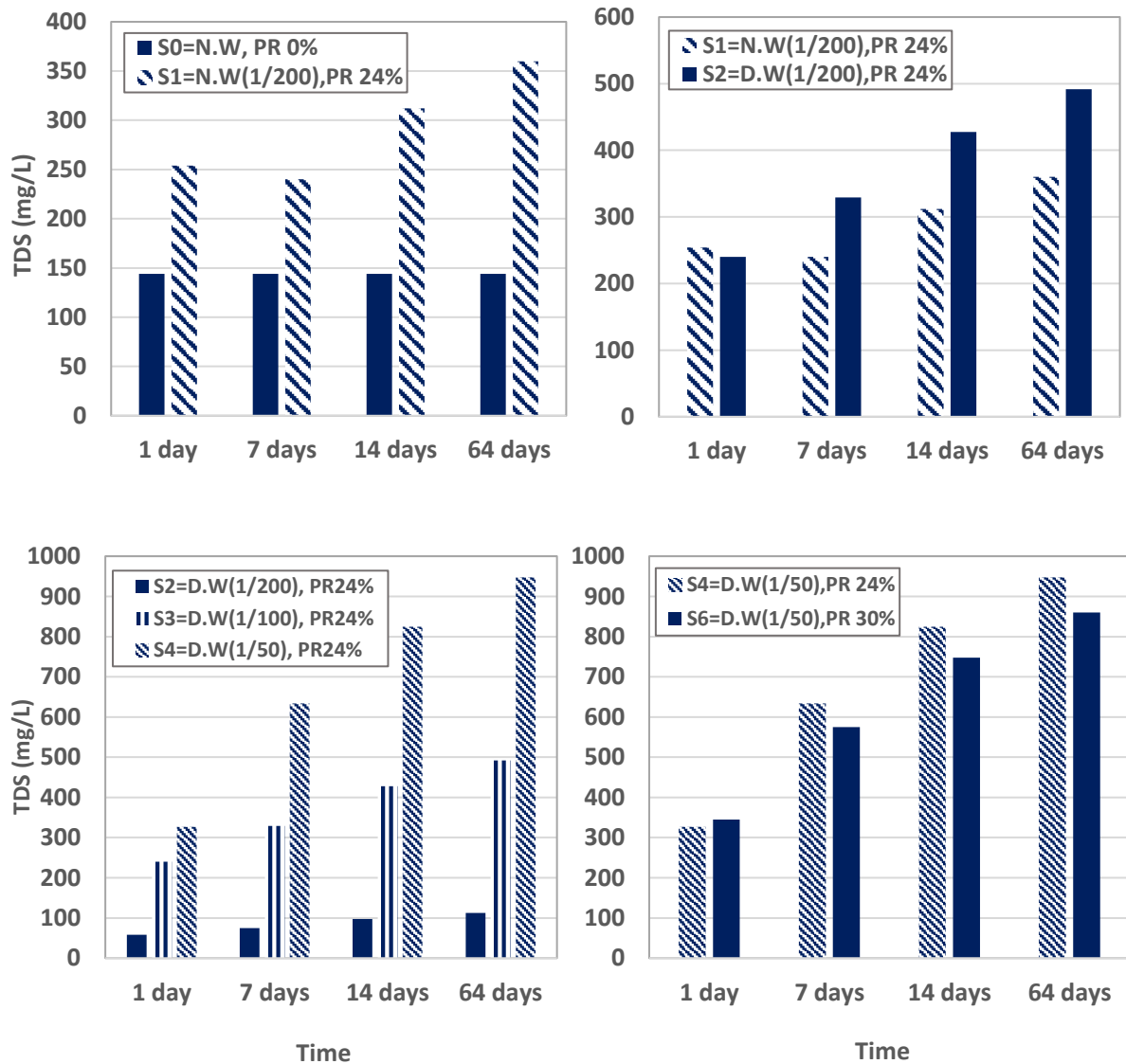


Figure 3. TDS measurements with time

Some studies showed that the solubility of PR is very low, and their leaching out is limited in the neutral pH water and increased with acidic waters [7; 12]. This study shows relatively high leaching properties for PR. This is perhaps due to the grinded PR samples were used and steering conditions applied to simulate the natural movements of water in streams such as Nile River.

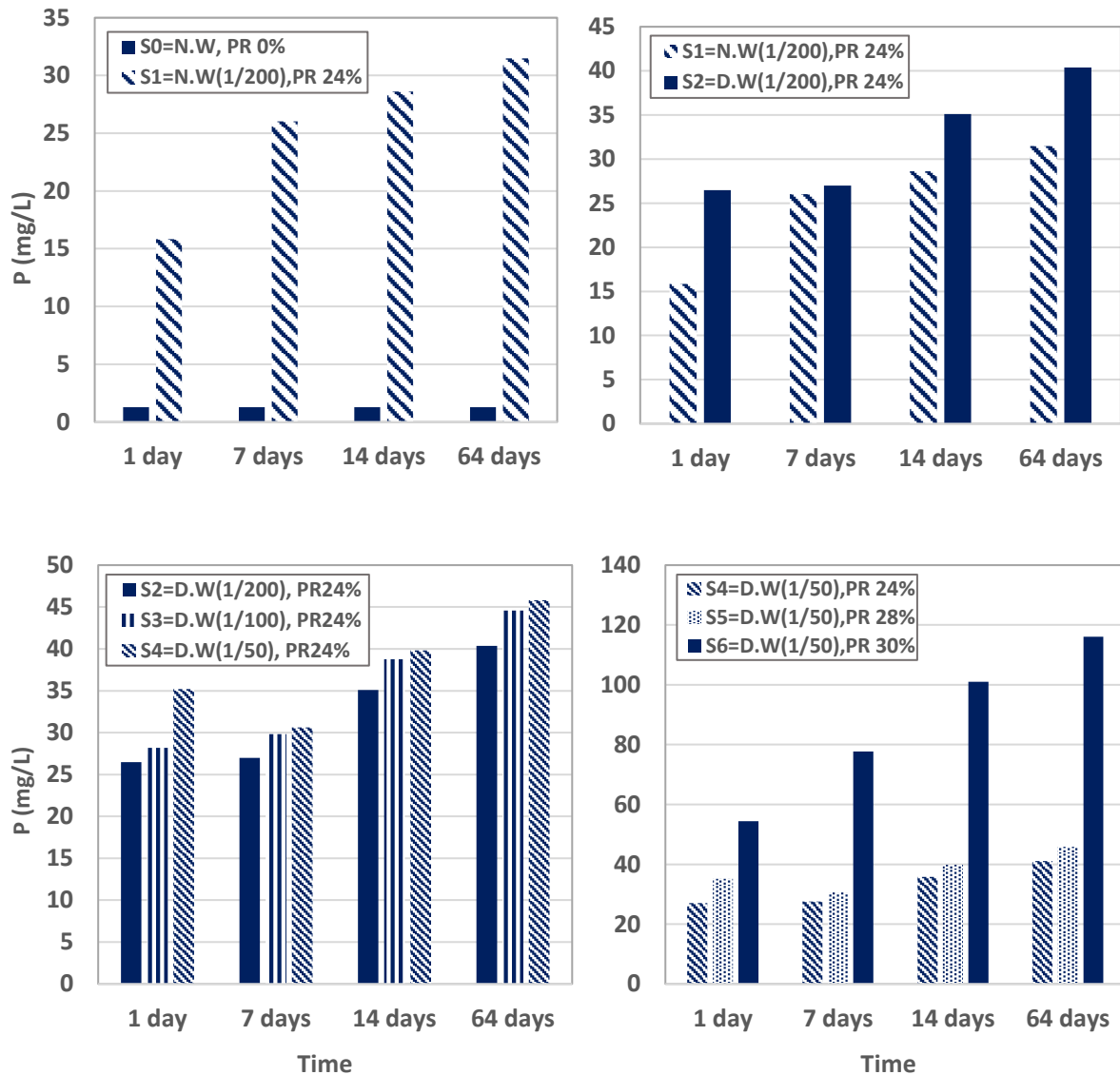


Figure 4. Phosphor release measurements with time

3.4 Heavy metals release

The heavy metals presence in natural streams has become an alarming topic worldwide in for water quality. The emphasis of this threatening concern is indirect harmfulness through accumulation of heavy metals in the aquatic food chain and direct poisonousness to human and aquatic life. Heavy metals such as chromium, lead, copper and zinc exhibit human toxicity at slightly higher concentrations while, cadmium at extremely low concentrations is toxic [13]. The results of this study, herein, showed that lead concentration released from PRs increased by 10% higher than the original content in Nile water after one day and reached 30% raise after 64 days. It increased with time and decreased with increase in L/S ratio. 30% P_2O_5 PR had higher lead release than 24%. Figure 5 presents lead release results.

For chromium and cadmium, which they were not shown in the figure, chromium release ranged between 0.01 to 0.03 mg/l in all samples and cadmium was 0.001 mg/l in some samples and not detected in most of the samples.

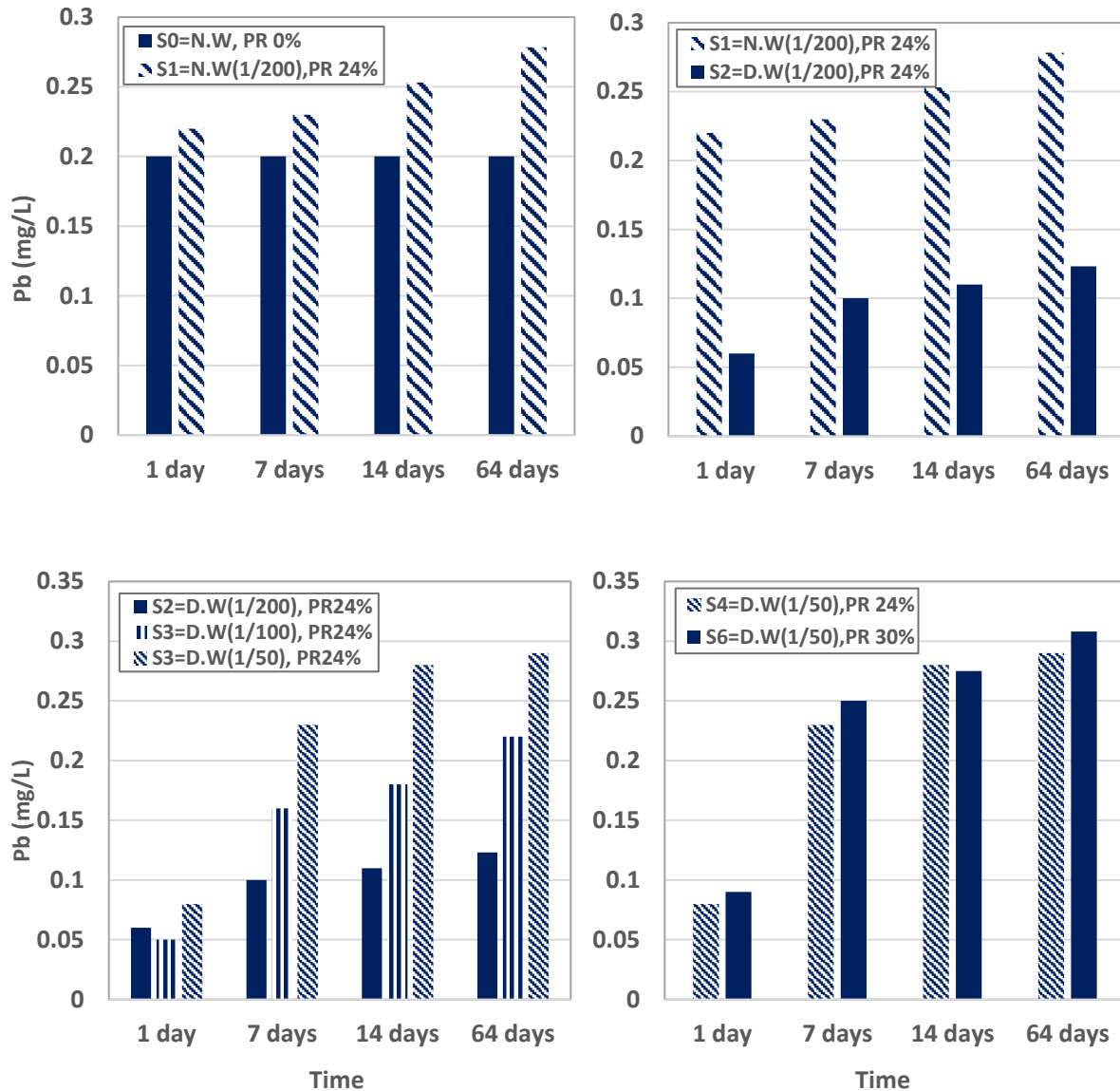


Figure 5. Lead release measurements with time

3.5 Overall Discussion

Phosphorus are nutrients for natural parts of aquatic ecosystems. Increase phosphorus with nitrogen from atmosphere supports the bloom growth of algae and aquatic plants, resulting in serious environmental and human health issues [10]. On the other hand, many health problems to human being are caused by increase phosphorus content, such as kidney damage and osteoporosis. According to the results discussed above, it is important to know if these values exceed the allowable value for drinking water and irrigation streams.

3.5.1 Water quality for Drinking:

World Health Organization [14] determined the allowable values of dissolved ions for safe drinking water as shown in Table 2. The table shows that in case of Nile water under conditions of 24% P₂O₅ PR and L/S ratio of 200, phosphor and lead were exceed greatly the allowable values for drinking water while the other parameter and elements were within permissible values. On other side, for distilled water samples under some extreme conditions of L/S ratios and P₂O₅ ratios in PR, all parameters and element contents close or above the allowable border of these values.

3.5.2 Water quality of irrigation streams: phosphorus element is regularly limited nutrient in freshwater streams. Therefore, if all phosphorus is consumed, growth of the plant will stop. The natural levels of phosphorus usually range from 0.005 to 0.05 mg/L. Increasing its available concentration lets plants to absorb more nitrogen before the phosphorus is exhausted. Consequently, if enough phosphorus is available, high concentrations of nitrates will lead to blooms in algal. Although levels of 0.08 to 0.10 ppm phosphorus may activate periodic blooms, but if total phosphorus levels are below 0.5 ppm, long-term nitrates richness will generally be avoided [15]. In this study, PRs leachate out 32 mg/L of phosphorus into Nile water. Therefore, according to the results of this study, if phosphate rocks are submersed intentionally or unintentionally into Nile river water, this will lead to environmental risks in the area of PR submersion. Similar results reported by Dushyanthaa et.al. [16] as they revealed that when PR incessantly exposed to weathering nearby lakes and streams, it can result in increasing their downstream sediments in both soluble and particulate phases of phosphorus. Thus, more studies are needed to investigate the transportation of these contaminations by the stream flow and self-purification ability of the Nile River in diluting and eliminating the impacts of these high concentrations.

Table 2. Allowable values for drinking water according to WHO (2011)

Parameter	EC (μ S/cm)	TDS (mg/l)	P (mg/l)	Pb (mg/l)	Cr (mg/l)	Cd (mg/l)
The highest reading after 64 days for Nile water sample	650	360	32	0.28	0.025	0.001
The highest reading after 64 days for distilled water samples	1770	940	117	0.31	0.03	0.001
WHO	1500	1000	0.015	0.05	0.05	0.003

4. Conclusion

The results of this study showed relatively high leaching properties for PR as it released significant amounts of different ions into water and this release continued with time.

In case of Nile water under conditions of 24% P_2O_5 PR and L/S ratio of 200, phosphor and lead were exceed greatly the allowable values for drinking water while the other parameters and elements such as chromium and cadmium were within the permissible values.

PRs leachate out 32 mg/L of phosphorus into Nile water, which is too, much more than the allowable values for natural streams, i.e. 0.5 mg/L. Therefore, if phosphate rocks are submersed intentionally or unintentionally into Nile river water, this will lead to environmental risks in the area of PR submersion.

More studies are needed to investigate the transportation of high levels of phosphor concentrations by the stream flow as well as self-purification ability of the Nile River in diluting and eliminating the impacts of these high concentrations.

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بسم الله الرحمن الرحيم و الصلاة و السلام على أشرف المرسلين سيدنا محمد و على آله وأصحابه
اجمعين. أما بعد،

فإنه يسعدني و يشرفني ان أقدم بين أيديكم الاصدار الثالث لسنة 1441 هـ من مجلة الجامعة الإسلامية
للعلوم التطبيقية. و لقد أنشأت هذه المجلة بهدف أن تجعل من صفحاتها ميداناً لكل ما هو جديد و
متميز من الأبحاث العلمية في مجالات الهندسة و العلوم و الحاسوب من شتى أنحاء البسيطة.

و تود هيئة التحرير و الهيئة الإستشارية أن تتقدم بخالص الشكر لكل من ساهم ببحثٍ أو مقالةٍ في
هذه المجلة. كما تسرها دعوة الباحثين للمساهمة في الأعداد القادمة بإذن الله.

فبكل فخر و إعتزاز اسمحوا لي أن أقدم إليكم العدد الثالث لهذه المجلة و أتمنى لكم قراءة ممتعة.

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قواعد النشر في المجلة (*)

- أن يكون البحث جديداً؛ لم يسبق نشره.
- أن يتسم بالأصالة والجدة والابتكار والإضافة للمعرفة.
- أن لا يكون مستقلاً من بحوثٍ سبق نشرها للباحث/للباحثين.
- أن تراعى فيه قواعد البحث العلميّ الأصيل، ومنهجيّته.
- أن يشتمل البحث على:
 - صفحة عنوان البحث باللغة الإنجليزية
 - مستخلص البحث باللغة الإنجليزية
 - صفحة عنون البحث باللغة العربية
 - مستخلص البحث باللغة العربية
 - مقدمة
 - صلب البحث
 - خاتمة تتضمن النتائج والتوصيات
 - ثبت المصادر والمراجع
 - الملاحق اللازمة (إن وجدت)
- في حال (نشر البحث ورقياً) يمنح الباحث نسخة مجانية واحدة من عدد المجلة الذي نشر بحثه، و (10) مستلّات من بحثه.
- في حال اعتماد نشر البحث تؤوّل حقوق نشره كافة للمجلة، ولها أن تعيد نشره ورقياً أو إلكترونياً، ويحقّ لها إدراجه في قواعد البيانات المحليّة والعالميّة- بمقابل أو بدون مقابل- وذلك دون حاجة لإذن الباحث.
- لا يحق للباحث إعادة نشر بحثه المقبول للنشر في المجلة- في أي وعاء من أوعية النشر- إلا بعد إذن كتابي من رئيس هيئة تحرير المجلة.
- نمط التوثيق المعتمد في المجلة هو نمط (IEEE).

(*) يرجع في تفصيل هذه القواعد العامة إلى الموقع الإلكتروني للمجلة:

<https://journals.iu.edu.sa/JESC/index.html>

معلومات الإيداع

النسخة الورقية:

تم الإيداع في مكتبة الملك فهد الوطنية برقم 8742 / 1439 وتاريخ 17 / 09 / 1439 هـ
الرقم التسلسلي الدولي للدوريات (ردمد) -7936-1658

النسخة الإلكترونية:

تم الإيداع في مكتبة الملك فهد الوطنية برقم 8742 / 1439 وتاريخ 17 / 09 / 1439 هـ
الرقم التسلسلي الدولي للدوريات (ردمد) -7944-1658

الموقع الإلكتروني للمجلة

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ترسل البحوث باسم رئيس تحرير المجلة إلى البريد الإلكتروني :
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(الآراء الواردة في البحوث المنشورة تعبر عن وجهة نظر الباحثين فقط، ولا تعبر بالضرورة عن رأي المجلة)

بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ



مجلة الجامعة الإسلامية

للعلوم التطبيقية

مجلة علمية دورية محكمة

1441 هـ

السنة: الثانية

العدد: 3