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A Novel IEC 61850-Based Protection Scheme to Maintain the Generator Synchronous Operation During Power System Disturbances

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Abstract: This study proposes an IEC 61850 based protection scheme to maintain the generator synchronous operation and prevent its tripping by the pole slipping protection (Relay 78) during system disturbances while the transmission line distance protection (R_{TL}) is blocked from operation. The scheme has been studied during common system disturbances, namely sudden load applications. This scheme could maintain the synchronous operation of the local generator and enable it to support the system during and after such disturbances; therefore, maintaining the system stability. A real recorded incidence of generator tripping by Relay 78 in the Egyptian grid is investigated and a new scheme to prevent such tripping during system disturbances is introduced. The new scheme takes the advantage of using IEC 61850 communication standard in coordinating the tripping role between Relay 78 and R_{TL}. This scheme can be applied based on the current technologies of protection relays. The scheme is modeled and simulated using MATLAB® Software and Xelas IEC 61850 simulator. The simulated system is configured according to the typical parameters of the Egyptian national grid 220 kV. Satisfactory results have proved the scheme effectiveness.

Key words: Generator pole slipping protection, GOOSE messages, IEC 61850, line distance protection, power swings, power system disturbances, protection scheme

INTRODUCTION

During steady state condition, a balance between the generated power and load demand is maintained for the power system stability. However, this balance is difficult to be maintained during system disturbances that cause oscillations across the system. Some of these disturbances can be ground faults, sudden load applications, symmetrical faults, wrong synchronization, open conductors, maneuvers, etc. Consequently, generating units should be adapted to a new load level to create a new balance point between the load demand and generated power. Depending on the seriousness of the disturbance and the relevant response of the system controls, the system may continue to be stable or face a large separation of generators rotor angles, thus causing in most cases a pole slipping of the connected generators and finally synchronism is lost. This pole slipping condition develops strong oscillations and affecting the network and the generators in a negative way (Fischer *et al*., 2012; Lamont and De Kock, 2015).

When the power system is unstable, a group of generators swings with respect to another generators group across the system. These swings wouldn't be observed by the network protection; thus, the need for pole slipping protection at the generator is necessary (Lamont and De Kock, 2015; Reimert, 2005). It is therefore important to have a protection system that can detect Out of Step (OOS) conditions and minimize the relevant consequences. This kind of protection is implemented by impedance relays whose impedance characteristics on the R-X diagram takes into account the impedance trajectory during a polar slip (Shrestha *et al*., 2013).

Recent outages of the generating units by the pole slipping protection during system disturbances have highlighted the necessity for new protection schemes to maintain the generator connected and avoid the relevant consequences during and after such events. The impact of power system disturbances on the generator protection performance has been reported in (Patel *et al*., 2004; Tziouvaras, 2007). The development of a predictive pole-slip protection function for synchronous generators has been reported in (Lamont and De Kock, 2015).

The proposed IEC 61850 based protection scheme can provide a beneficial coordination between Relay 78 and transmission line distance protection (R_{TL}) through GOOSE communications in order to trip the specific transmission line suffering power swing oscillations, therefore, the generator synchronous operation is maintained to supply other connected loads such as Tie-transformers and other lines during and after system disturbances.

The performance of Relay 78 and R_{TL} after implementing the proposed scheme is studied in this study during a sudden large load application. The following items are the contributions of this study:

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It highlights the possibility of avoiding the generator tripping by Relay 78 during system disturbances by tripping instead the transmission line suffering power swing oscillations.

It is believed to be the first IEC 61850 based protection scheme used in both Relay 78 and R_{TL} to achieve the above solution.

Generator pole slipping: Pole slipping mode is an issue for synchronous generators operated in parallel with electrical systems (Lamont and De Kock, 2015; Redfern and Checksfield, 1998). it caused by the system disturbances such as severe faults, sudden load variations, long fault clearing time, line switching, etc. (Redfern and Checksfield, 1998). In such cases, the system may continue to have a stable operation or face large power oscillations that lead to pole slipping mode in one or more generators in the system (Lamont and De Kock, 2015). Generator pole slipping causes high fluctuations of generator's currents which are causes high fluctuations in system voltages. Besides, the magnitude of currents experienced during a pole slipping can exceed the levels of 3 phase fault, these high currents lead to thermal and mechanical stresses on the generator's windings (Redfern and Checksfield, 1998). Thus, the generators must be tripped and disconnected from the system quickly as possible after loses its synchronous operation with the electrical power system. Therefore, it is important to implement pole slipping protection to synchronous generator (Lamont and De Kock, 2015; Redfern and Checksfield, 1995).

Pole slipping protection: Relay 78 is set to provide protection against generator pole slipping. The most widely applied methods for detecting generator pole slipping monitor the change in the apparent impedance seen from the generator terminals (Imhof *et al*., 1977). Various types of characteristics can be used such as Mho or a lenticular characteristic with one or two blinders in order to increase the selectivity (Burek *et al*., 2012). In this regard, the Mho characteristic with the single blinder scheme is used during the investigations of this study. The voltage and current fluctuations appeared during pole slipping conditions cause the impedance trajectory seen by Relay 78 to move from the right (loading point) into left and enter to Relay 78 characteristics between the blinders. Thus, if the time needed to cross the right and left detecting blinders exceeds a pre-defined time setting of Relay 78 (t_{78}), a tripping signal is issued to trip the generator (Fischer *et al*., 2012).

The forward reach setting for the mho characteristic of Relay 78 is chosen from 2-3 times of the generator transient reactance (X'_d); while the offset setting is chosen from 1.5-2 times of transformer impedance (X_t) (Reimert, 2005). In this respect, the settings considered in this study are selected to match the setting values considered in the Egyptian power plants as follows:

- The setting of mho diameter (Z78) = $1.5\ X_t+2X'_d$
- The setting of offset = $1.5X_t$
- The setting of the blinder angle (θ) = 90°
- The setting of blinder impedance = $1/(2(X'_d+X_t+X_S)\tan(\theta-0.5\delta))$. Where X_S is a system reactance and δ is the angle between the generator and system voltage
- The setting of time delay = 6 cycles

Transmission line distance protection (R_{TL})

Characteristics of R_{TL}: The R_{TL} is used to protect the transmission line against faults. The operation of this kind of protection depends on calculating the line impedance using voltage and current signals measured by the voltage and current transformers and compares it with its pre-defined setting values to determine the faulted zone on the line (Ziegler, 2011). The characteristics of R_{TL} on the R-X diagram show the impedance trajectory and specify the response of R_{TL}. Many different types of characteristics are used for R_{TL}, such as the lens, mho, quadrilateral and tomato (Rincon and Perez, 2012).

R_{TL} possibly responds to the fluctuations of voltage and current caused by stable power swings and provides unwanted tripping for the line. This action may lead to cascading outages (Khodaparast and Khederzadeh, 2016). Therefore, it is important to block R_{TL} during stable power swing by using a Power Swing Blocking function (PSB) to avoid any unwanted relay operation (Fischer *et al*., 2012). Many techniques are used to detect the power swings. In this respect, the mho type distance protection with the concentric characteristic scheme is considered during the investigation of this study. The operating principle of this scheme is based on measuring the traveling time of the impedance trajectory seen by R_{TL} between the inner and outer scheme's characteristics shown on the R-X diagram. A stable power swing oscillation is detected if the impedance trajectory remains between the inner and outer scheme's characteristics for a time longer than a pre-defined time delay. Thus, the PSB will operate and block the operation of R_{TL} (selected zones) for a pre-defined time. On the other hand, during Out-of-Step (OOS) conditions (unstable power swings), OOS tripping signal is issued to trip the line (Mooney and Fischer, 2006).

Setting of R_{TL}: Typically, three protection zones are determined for R_{TL} to provide protection for the line and next sections (Rani and Sridevi, 2016). The strategy of R_{TL} settings that is considered by the Egyptian grid authority is summarized as follows (Gilany *et al*., 2000):

- The first zone (Z1) is adjusted to protect 80% of the TL length with no time delay
- The second zone (Z2) is adjusted to protect 100% of the TL length plus 40% of the next shortest line length. The associated time delay (t_2) is adjusted at 0.5 sec
- The third n zone (Z3) is adjusted to protect 100% of the TL length plus 100% of the next shortest line section plus a 20% of the second shortest line length following the protected line. The associated time delay (t_3) is adjusted at 1 sec

Problem formulation: Electrical systems are exposed to different disturbances that can cause oscillations in the generator rotor angle. These oscillations translate into power swings over the system. The delay of disturbance clearing time determine if these swing oscillations will be stable or unstable (Fischer *et al*., 2012). During a stable swing oscillation, it is possible that the impedance trajectory will penetrate the operating characteristics of R_{TL} and cause an unwanted line tripping by $R_{TL.}$ In this event, R_{TL} needs to be blocked using its power swing blocking function to avoid the unwanted tripping during such events (Fischer *et al*., 2012; Mooney and Fischer, 2006).

According to the system topology, the power swing may grow across the system and impact the synchronous operation of local generator and thus lead to generator pole slipping. Indeed, these issues may occur within a short time, while R_{TL} is still blocked from the operation. A typical recorded incidence in the Egyptian grid has faced the same conditions where Relay 78 picked up and tripped the generator after timing out its time delay as shown in Fig. 1. However, R_{TL} doesn't trip as shown in

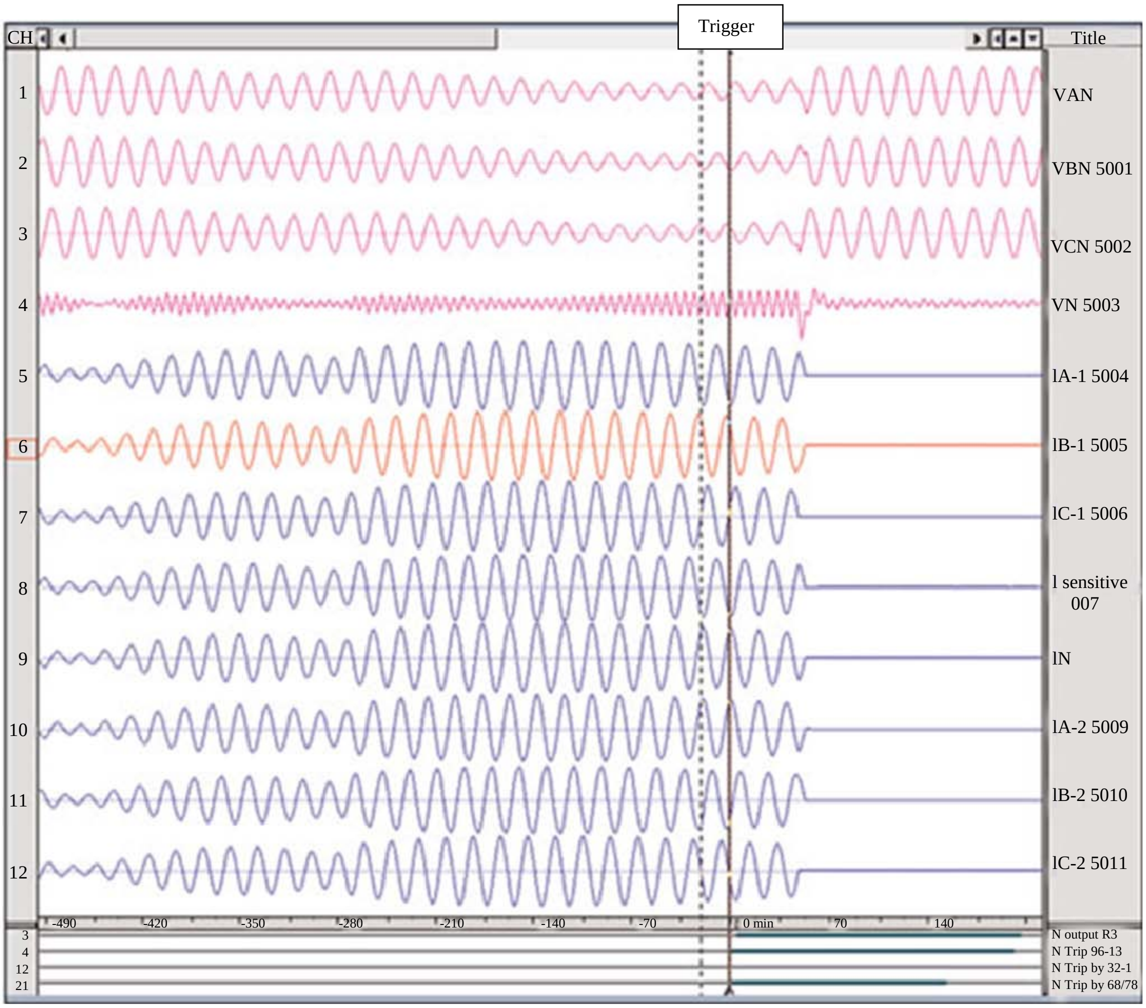


Fig. 1: Actual record by Relay 78 for generator pole slipping condition occurred as a result of the mentioned incidence

Fig. 2. In such incidences, it is necessary to separate the overall system at pre-defined locations (determined by stability studies) into several independent systems as rapidly as possible with the creation of system islands to prevent blackouts (Fischer *et al*., 2012). Thus, load shedding or disconnecting of non-important generating

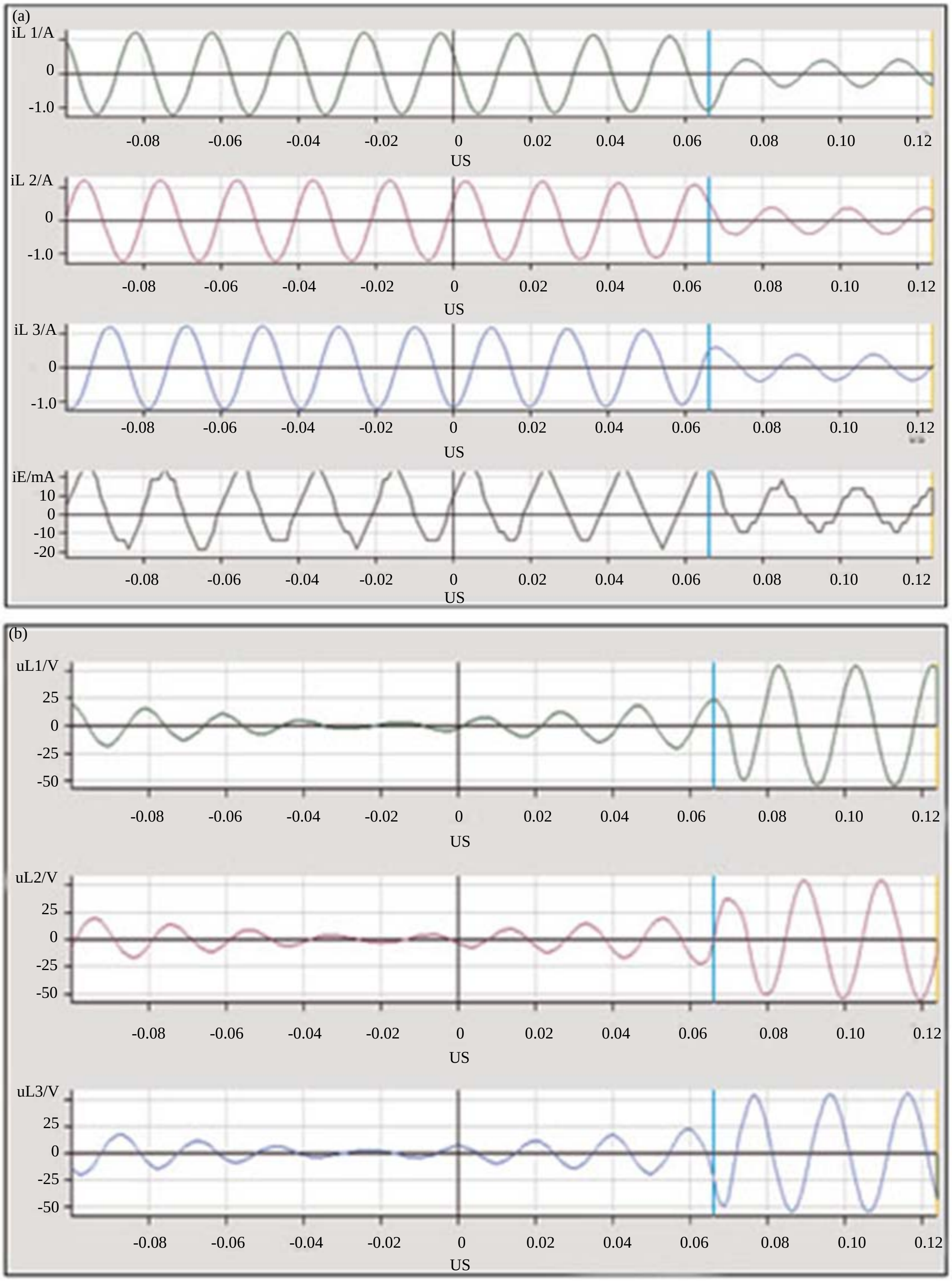


Fig. 2(a-c): Continue

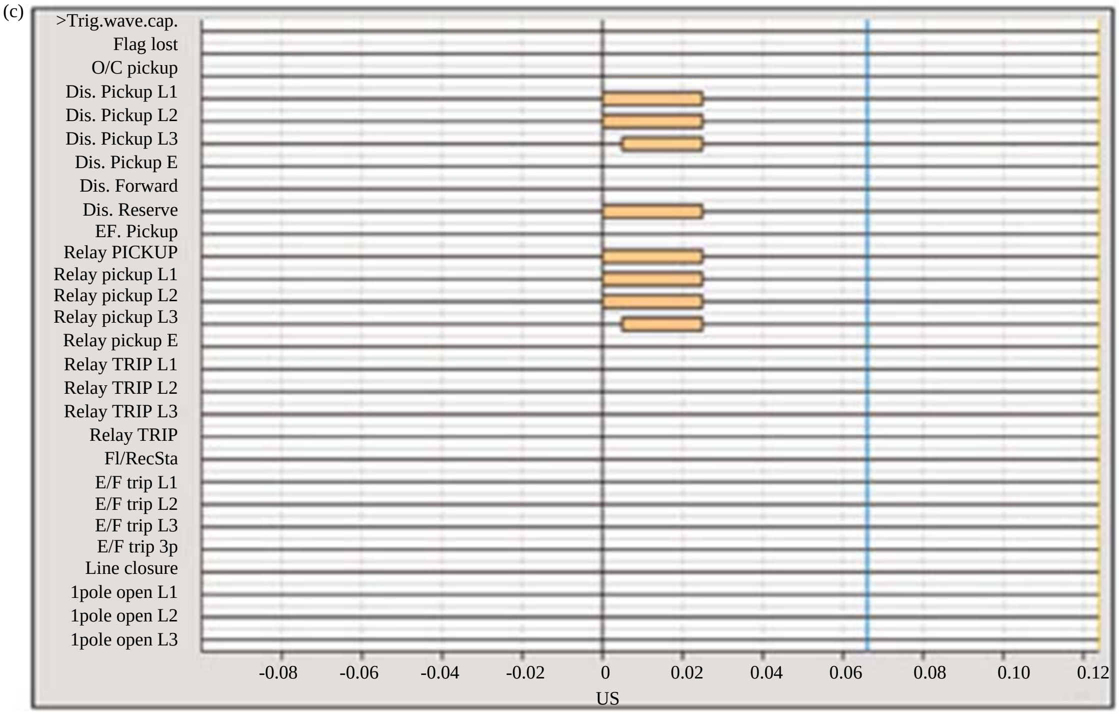


Fig. 2(a-c): Actual record by R_{TL} for the power swing occurred as a result of the mentioned incidence (a) TL currents, (b) TL voltages and (c) R_{TL} triggered elements

units may be executed to prevent a complete shutdown of each island. Finally, all these consequences will impact the power system.

IEC 61850 GOOSE protocol: The IEC 61850 standard for substations enables the integration of all protection, control, measurement and monitoring functions. These functions require high speed and reliable communications in the substations. Traditionally, this was achieved using copper wires between the control station and IEDs and between the IEDs in the substation. However, using copper wires for communication creates a very complex network of wires inside the substation. Now, Ethernet-based Local Area Network (LAN) provides reliability, better speed and is easy to maintain (Fernandes *et al*., 2014).

As a LAN based protocol, Generic Object Oriented Substation Event (GOOSE) is reliable for event and status exchange between IEC 61850 based IEDs either for protection or for control. Some critical control operations (such as interlocking and auto-reclosing signals) as well as protection related signals (such as trip and blocking) utilize IEC 61850-8-1 communication service for event and status delivery within real-time protection and control facilities. Performing real-time delivery GOOSE communications offers time-critical features by using the Ethernet (IEEE 802.3) multicasting paradigm (Fernandes *et al*., 2014).

The IEC 61850 states that the signal of interest (which is “Trip” or “Block Trip” in this study) has to be transmitted continuously on the network by the relevant IED. On the other hand, IED needing this signal has to read it in the proper time. This transmitting IED is called “Publisher” while the IED that should get the transmitted information is called “Subscriber” (IEC., 2010). The GOOSE message is retransmitted at a steady frequency until the GOOSE data changes. At that time, the original stream stops and a new message is generated immediately at very high frequency. Figure 3 below shows the GOOSE conceptual mechanism.

Proposed scheme: A proposed communication-based protection scheme is introduced to coordinate between the R_{TL} and Relay 78 through an IEC 61850 based GOOSE communications as shown in Fig. 4. This scheme coordinates the role of tripping between R_{TL} and Relay 78 during the system disturbances, thus, the tripping of local generator by Relay 78 can be avoided. Therefore, the performance of R_{TL} and Relay 78 is enhanced, being smarter in dealing with the system dynamics.

The philosophy of this scheme is based on detecting the movement of impedance trajectory on R-X diagram from the generator loading point location to Relay 78 characteristics during system disturbances while R_{TL} of the line suffering oscillations is blocked from operation.

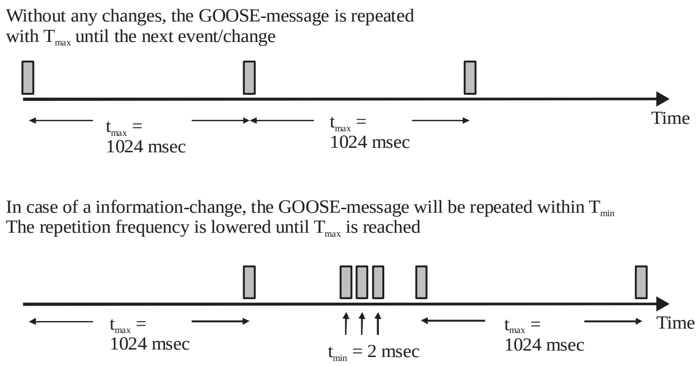


Fig. 3: GOOSE messaging mechanism

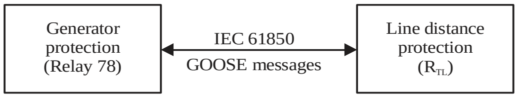


Fig. 4: Coordination between R_{TL} and relay78 using IEC 61850 GOOSE messages

During such events, Relay 78 sends a direct tripping order to R_{TL} via a GOOSE messages to force it trip the line suffering oscillations. As a result, the path of swing oscillation through TL is cut; thus, the oscillations will disappear and the impedance trajectory seen by Relay 78 jumps outside its characteristics and leaves to the loading region on the R-X diagram as shown in Fig. 10. Consequently, the pickup status of Relay 78 is released as it eventually sees a healthy conditions. This will help the local generator recover its normal operation and prevent the growth of oscillations (causing serious consequences) over the system. Figure 5 shows a flow chart representing the scheme operation during a disturbance caused by a sudden load application.

System under study: To investigate the performance of the proposed scheme in maintaining the generator synchronous operation during the disturbance caused by a sudden load application, a real part of the Egyptian grid (220 kV) that has faced such disturbance is used in this study as a system model with real parameters as shown in Fig. 6. This model contains the generator of El-Tibin power plant (437 MVA, 21 kV turbo generator) connected via a generator step-up transformer (GSUT 480 MVA, 21/220 kV) to an infinite-bus system through a 220 kV, 140 km TL. The detailed parameters of this model are given in the Appendix. The simulations performed for this model have been carried out using the MATLAB® Software and Xelas IEC 61850 simulator.

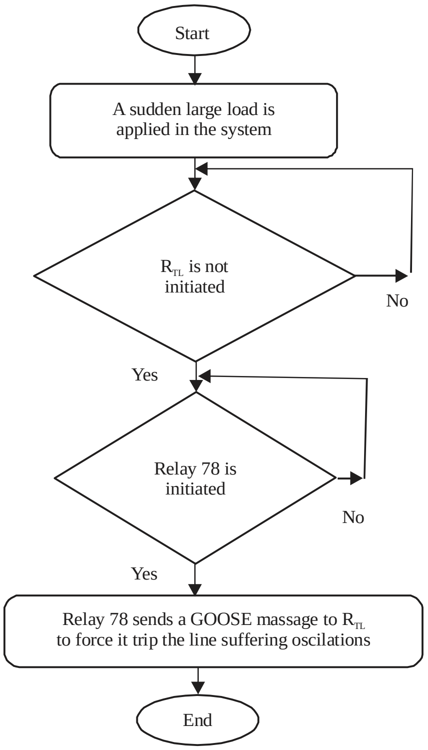


Fig. 5: Operation of the proposed scheme

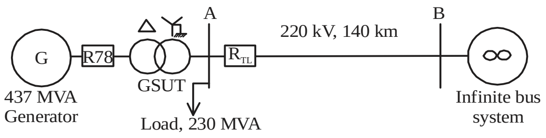


Fig. 6: Model of the system under study

Although, the above model is used in this study for simulation purpose, the proposed scheme can be applied in the more common case of having more than one generator in the power plant where all are connected to the grid through a number of transmission lines.

Characteristic of relay 78: Figure 7 shows the characteristic of Relay 78 on the R-X diagram. The impedance reach of Relay 78 (Z78) is set at 10.82 Ω with offset 3.12 Ω and the blinder impedance is set at 1.8 Ω at blinder angle (θ) = 90°. However, the time delay of Relay 78 (t_{78}) is set at 6 cycles.

Characteristic of R_{TL}: Figure 8 shows the characteristic of R_{TL} on the R-X diagram at MTA = 80°. Z1 is set at 33.89 Ω with no time delay; Z2 is set at 50.8 Ω with time delay 0.5 sec; Z3 is set at 65 Ω with time delay 1 sec. Moreover, the outer characteristic of PSB function surrounds the reach of the largest Zone (Z3) by ΔZ = 5 Ω (to match the setting considered in the numerical distance relays) (Ziegler, 2011).

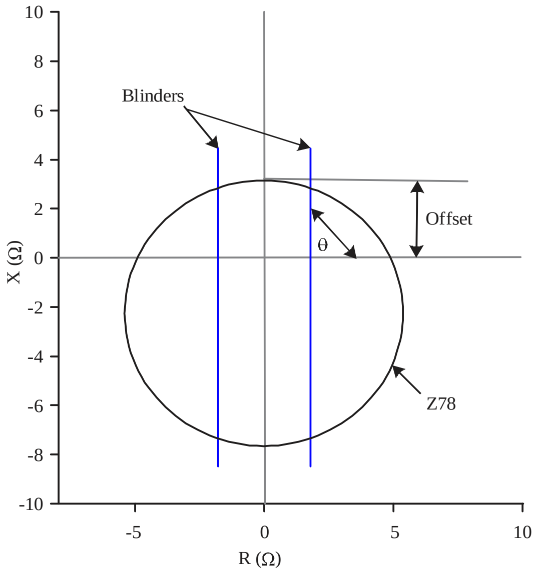


Fig. 7: Relay 78 characteristic on the R-X diagram

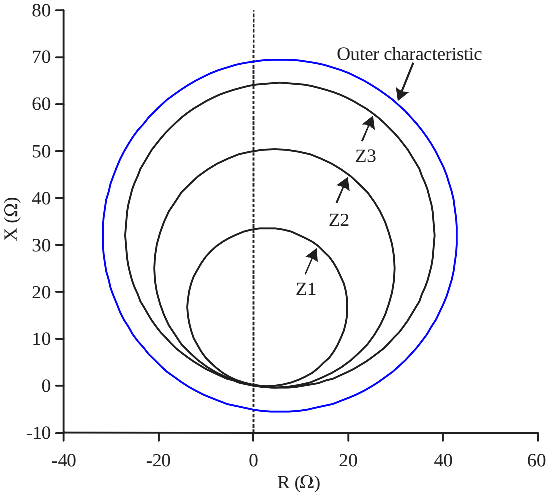


Fig. 8: Zones of R_{TL} with the concentric characteristic

RESULTS AND DISCUSSION

The proposed scheme's performance is investigated in this study during a disturbance caused by a sudden load application (1400 MVA) at bus B at t = 6.65 sec. However, the pre-fault condition of the generator (loading condition) is considered to be at least 80% of its rated apparent power (MVA) as per the recommendation of WSCC (2000). In response to the disturbance caused by this sudden load application at bus B, power swings are created in the system and causes oscillations in generator voltages and currents as shown in Fig. 9.

Response of Relay 78 during the disturbance: In response to the oscillations of generator voltages and currents caused by the disturbance, the impedance trajectory seen by Relay 78 penetrates its characteristic and the right blinder as shown in Fig. 10. Thus, Relay 78 picks up and its timer starts. For the purpose of avoiding the generator tripping by Relay 78 while R_{TL} is blocked from operation, GOOSE messages are sent from Relay 78 to R_{TL} to force it trip directly the line suffering oscillations at t = 8.96 sec before timing out the timer of Relay 78 (t_{78}). Consequently, the path of swing oscillations through the line will be cut and the oscillation will disappear as shown in Fig. 11. Finally, the impedance trajectory seen by Relay 78 moves outside its characteristic towards a

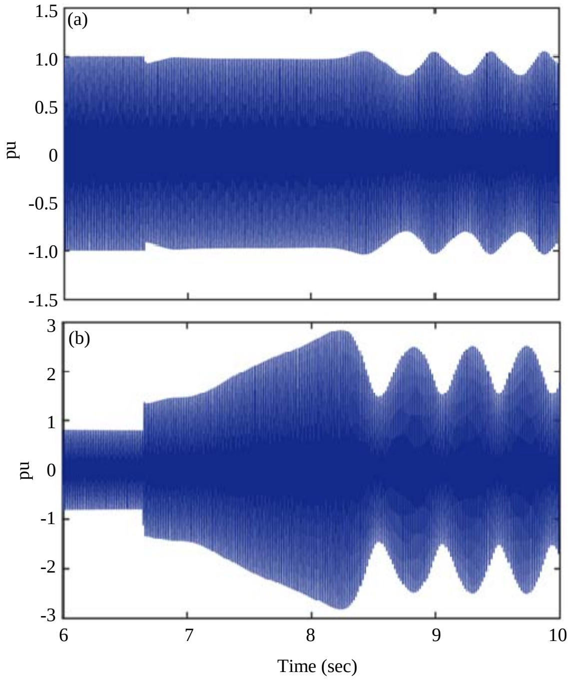


Fig. 9(a-b): Voltage and current oscillations during the disturbance (a) Generator voltages and (b) Generator currents

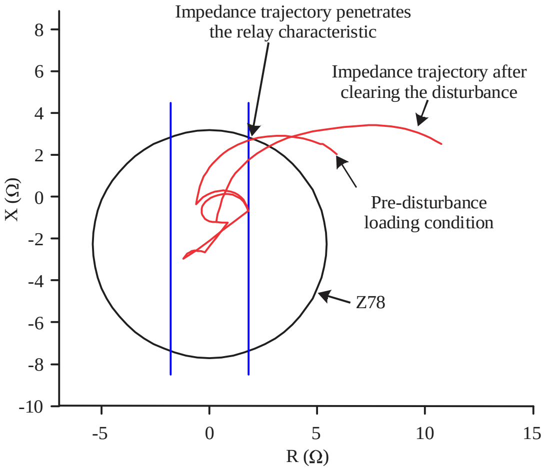


Fig. 10: Impedance trajectory seen by Relay 78 during and after the disturbance

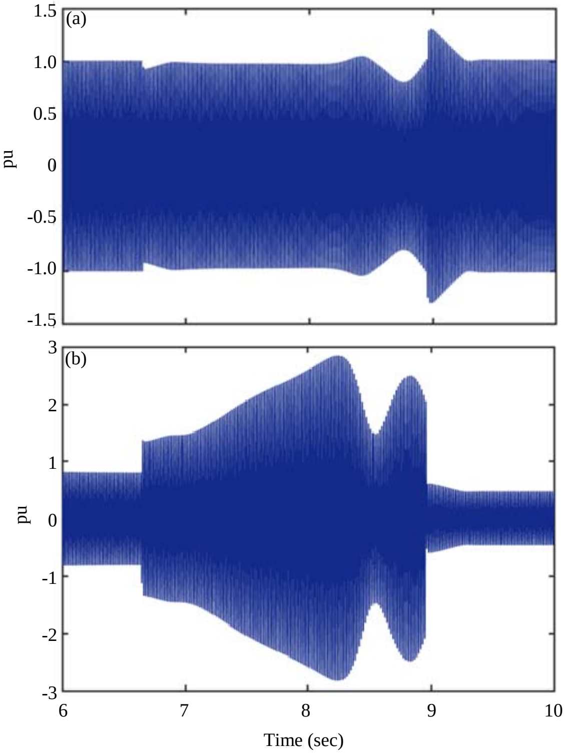


Fig. 11(a-b): Generator voltages and currents during and after the disturbance (a) Generator voltages and (b) Generator currents

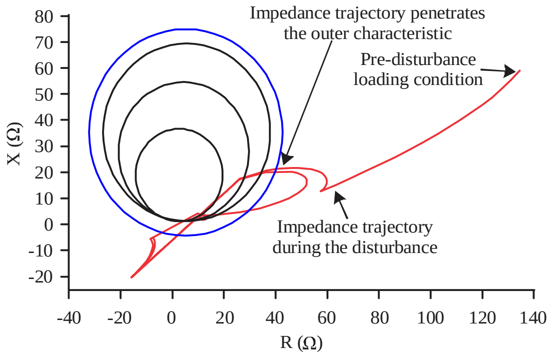


Fig. 12: Impedance trajectory seen by R_{TL} during the disturbance

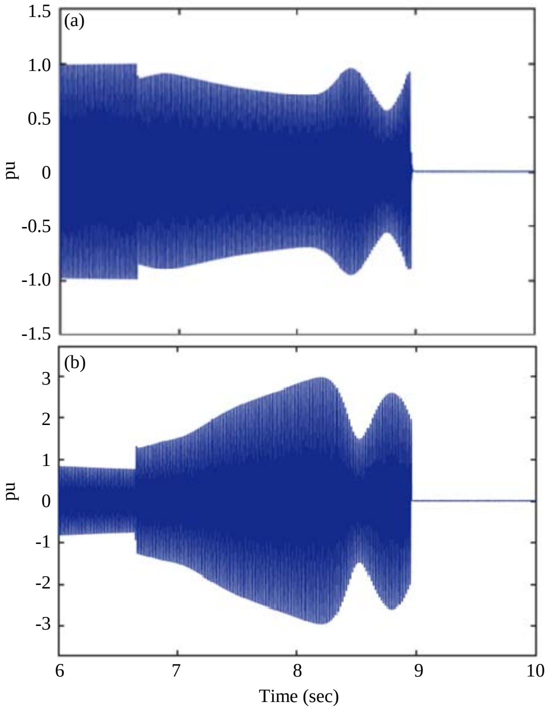


Fig. 13(a-b): TL voltages and currents during and after the disturbance (a) TL voltages and (b) TL currents

new loading point on the R-X diagram as shown also in Fig. 10. Therefore, Relay 78 doesn't trip the generator and its pickup status is released.

Response of R_{TL} during the disturbance: In response to the power swing oscillations caused by the disturbance, the impedance trajectory seen by R_{TL} will move toward its characteristics passing through the outer characteristic then moves again out and in of R_{TL} characteristics on the R-X diagram as shown in Fig. 12. In this case, the rate of resistance change of the impedance trajectory is smaller than the predefined setting value and thus, PSB function will operate and block the operation of R_{TL} (As per the setting considered in the Egyptian grid, PSB is set to block all zones of R_{TL} for 2 sec). Since, it is desired to preventthe generator tripping by Relay 78 during the disturbance, R_{TL} will respond to the published GOOSE messages by Relay 78 at t = 8.96 sec and provide instantaneous tripping to the line suffering oscillations. Consequently, the oscillations are disappeared as shown in Fig. 13.

Proposed IEC 61850 based scheme: If power swing oscillations occur and grow over the system, the element “Out Of Step Operate” in Relay 78 will be set to “True”. To prevent the generator from being tripped by Relay 78 during power swing oscillations and to trip instead the breaker of the line suffering oscillations instead by R_{TL}, the generator Protection Trip Conditioning logical node (PTRC) will refrain from tripping and a GOOSE message will be published with the “Generator Out Of Step Operate value = True” to R_{TL} and triggering its PTRC logical node to trip the line breaker directly. Figure 14 shows the logic implemented in this study deploying GOOSE.

The above scheme has been implemented on IEC 61850 IED simulator “Xelas Energy”, where the Configured IED Description (CID) file of R_{TL} is run on one PC while Relay 78 is run with the same CID file on another PC. Both PCs are linked via. a direct Ethernet cable.

In order to detect the response of the simulated R_{TL}, the logical output (Direct R_{TL} Trip) will be mapped to an output GOOSE message via. the R_{TL} simulator. Both GOOSE messages published by the R_{TL} and Relay 78 will be monitored and analyzed by the Wireshark Network Analyzer. This analyzer will run on the R_{TL} simulator PC. Figure 15 shows a snapshot of the distance protection CID file running as a server on both machines.

Enabling GOOSE on the generator protection device: The proposed scheme utilizes GOOSE messages to convey the Boolean value of the data attribute (EWL03_P442Control/PsbRPSB1.Op.ST.general) of Relay 78 to R_{TL}. This attribute as defined by IEC 61850 (either true or false) refers to the generator out of step function (Relay 78) whether it operates or not. Figure 16 shows the Operate (Op) data object with its attributes.

The published GOOSE stream is shown in Fig. 17, where the steady-state transmission (the out of step does not operate) is displayed in the first 18 packets. When the out of step element (Relay 78) operates, a new stream starts from packet number 19 as shown in the same figure.

According to the logic shown in Fig. 14, if the GOOSE messages received by R_{TL} gives true value (Tr) of Out of step (Relay 78) operate (Data attribute: EWL03_P442Control/PcbRPSB1.Op. ST. general = 1), R_{TL} will issue a direct trip to the line breaker and simultaneously publish GOOSE stream starting from packet 24 as shown in Fig. 17. Figure 18 and 19 provide a detailed view of GOOSE packets number 19 and 24.

Using the Wireshark analyzer, the graph of GOOSE packets versus time can be obtained. Figure 20 shows the initiating and triggered packets of the Relay 78 and the R_{TL} respectively, where the time span between the two events is about 177 msec.

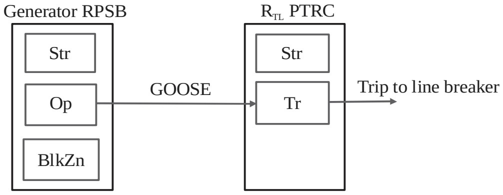
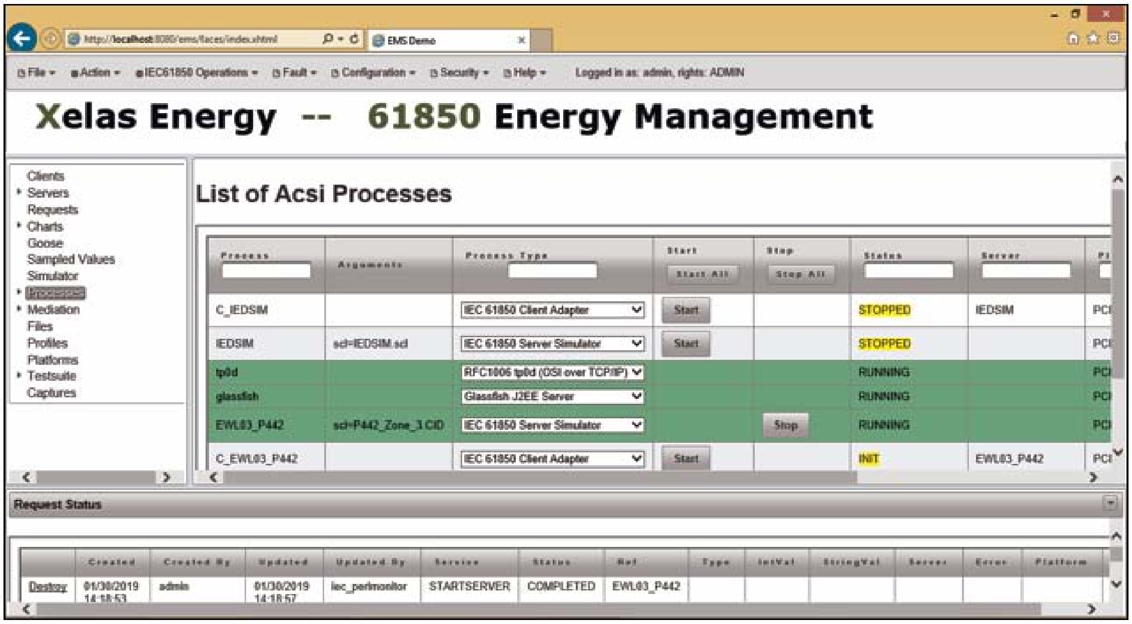


Fig. 14: Relay 78 Logical Node (RPSB) communicating direct trip GOOSE to R_{TL} Logical Node (PTRC)



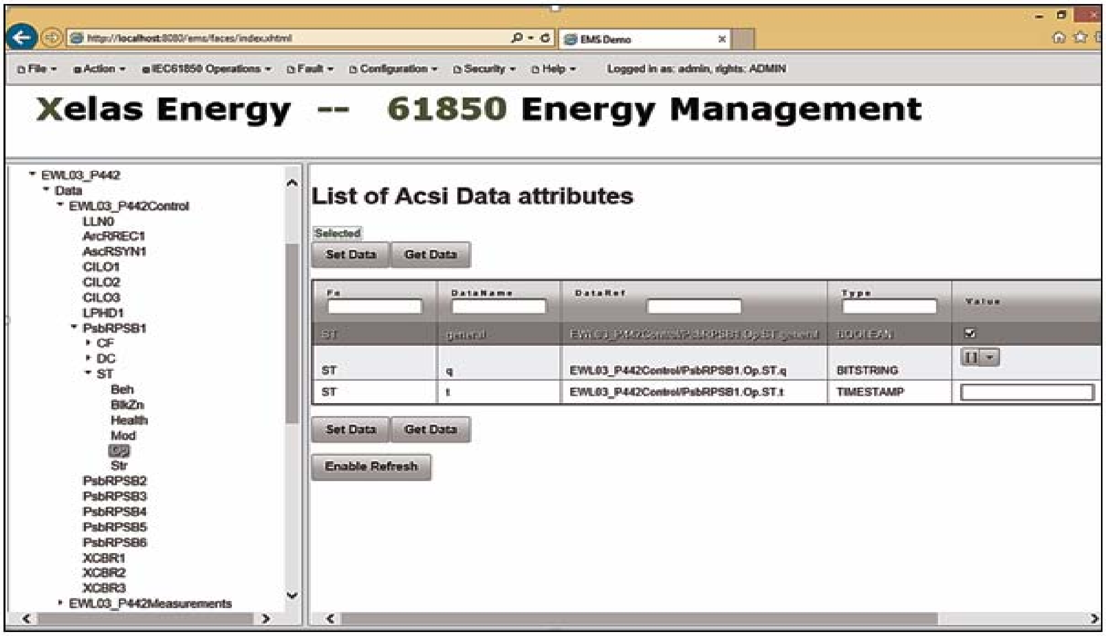
List of Acsi Processes

Process	Arguments	Process Type	Start	Stop	Status	Server	Pl
C_IEDSIM		IEC 61850 Client Adapter	Start		STOPPED	IEDSIM	PCI
IEDSIM	scl=IEDSIM.scl	IEC 61850 Server Simulator	Start		STOPPED		PCI
tp0d		RFC1006 tp0d (OSI over TCP/IP)			RUNNING		PCI
glassfish		Glassfish J2EE Server			RUNNING		PCI
EWL03_P442	scl=P442_Zone_3.CID	IEC 61850 Server Simulator		Stop	RUNNING		PCI
C_EWL03_P442		IEC 61850 Client Adapter	Start		INIT	EWL03_P442	PCI

Request Status

	Created	Created By	Updated	Updated By	Service	Status	Ref	Type	IntVal	StringVal	Server	Error	Platform
Destroy	01/30/2019 14:18:53	admin	01/30/2019 14:18:57	iec_perfmonitor	STARTSERVER	COMPLETED	EWL03_P442						

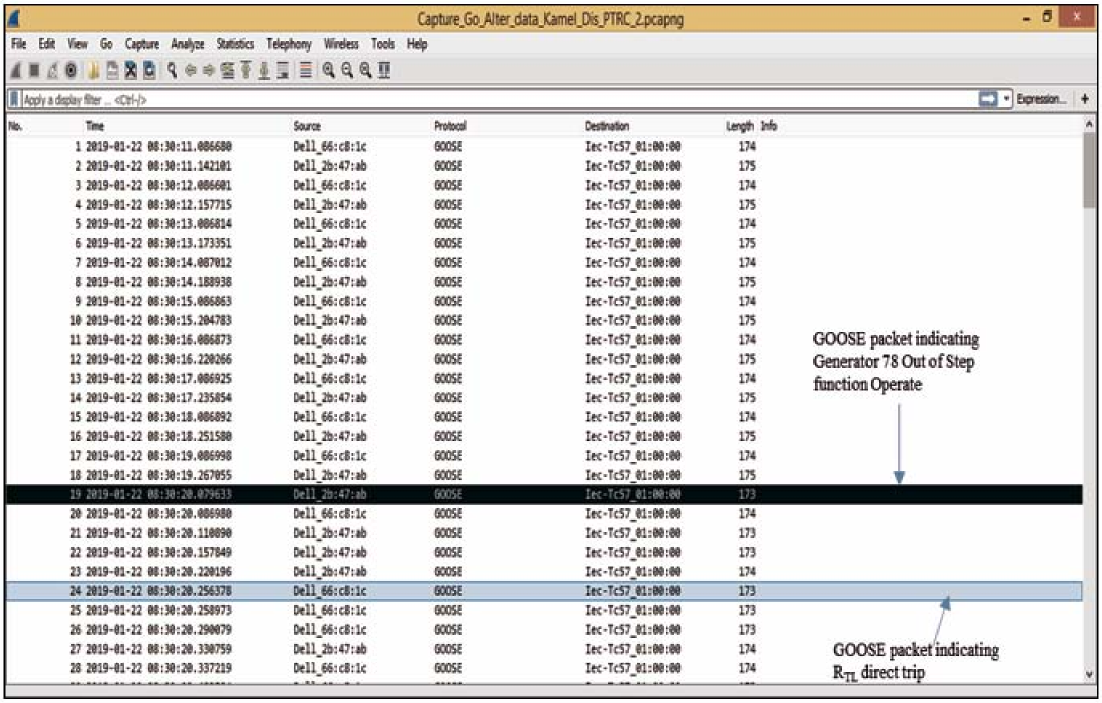
Fig. 15: Distance protection EWL03_P442 server running



List of Acsi Data attributes

Fc	DataName	DataRef	Type	Value
ST	general	EWL03_P442Control/PsbRPSB1.Op.ST.general	BOOLEAN	☑
ST	q	EWL03_P442Control/PsbRPSB1.Op.ST.q	BITSTRING	[]
ST	t	EWL03_P442Control/PsbRPSB1.Op.ST.t	TIMESTAMP	

Fig. 16: Generator out of step operation element composition



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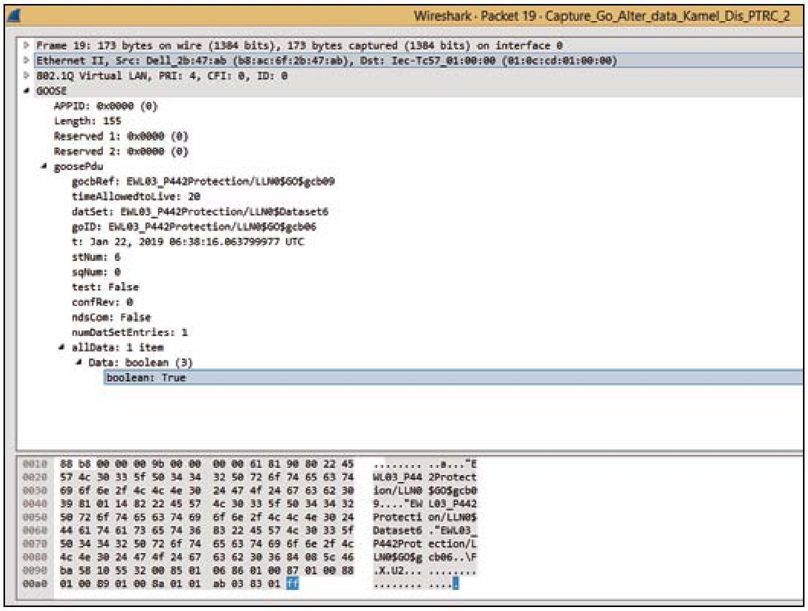
No.  Time                           Source           Protocol  Destination          Length  Info
   1 2019-01-22 08:30:11.006680     Dell_66:c8:1c    GOOSE     Iec-Tc57_01:00:00    174
   2 2019-01-22 08:30:11.142101     Dell_2b:47:ab    GOOSE     Iec-Tc57_01:00:00    175
   3 2019-01-22 08:30:12.006601     Dell_66:c8:1c    GOOSE     Iec-Tc57_01:00:00    174
   4 2019-01-22 08:30:12.157715     Dell_2b:47:ab    GOOSE     Iec-Tc57_01:00:00    175
   5 2019-01-22 08:30:13.006814     Dell_66:c8:1c    GOOSE     Iec-Tc57_01:00:00    174
   6 2019-01-22 08:30:13.173351     Dell_2b:47:ab    GOOSE     Iec-Tc57_01:00:00    175
   7 2019-01-22 08:30:14.007012     Dell_66:c8:1c    GOOSE     Iec-Tc57_01:00:00    174
   8 2019-01-22 08:30:14.188938     Dell_2b:47:ab    GOOSE     Iec-Tc57_01:00:00    175
   9 2019-01-22 08:30:15.006863     Dell_66:c8:1c    GOOSE     Iec-Tc57_01:00:00    174
  10 2019-01-22 08:30:15.204783     Dell_2b:47:ab    GOOSE     Iec-Tc57_01:00:00    175
  11 2019-01-22 08:30:16.006873     Dell_66:c8:1c    GOOSE     Iec-Tc57_01:00:00    174
  12 2019-01-22 08:30:16.220266     Dell_2b:47:ab    GOOSE     Iec-Tc57_01:00:00    175
  13 2019-01-22 08:30:17.006925     Dell_66:c8:1c    GOOSE     Iec-Tc57_01:00:00    174
  14 2019-01-22 08:30:17.235854     Dell_2b:47:ab    GOOSE     Iec-Tc57_01:00:00    175
  15 2019-01-22 08:30:18.006892     Dell_66:c8:1c    GOOSE     Iec-Tc57_01:00:00    174
  16 2019-01-22 08:30:18.251580     Dell_2b:47:ab    GOOSE     Iec-Tc57_01:00:00    175
  17 2019-01-22 08:30:19.006998     Dell_66:c8:1c    GOOSE     Iec-Tc57_01:00:00    174
  18 2019-01-22 08:30:19.267055     Dell_2b:47:ab    GOOSE     Iec-Tc57_01:00:00    175
  19 2019-01-22 08:30:20.079633     Dell_2b:47:ab    GOOSE     Iec-Tc57_01:00:00    173
  20 2019-01-22 08:30:20.006980     Dell_66:c8:1c    GOOSE     Iec-Tc57_01:00:00    174
  21 2019-01-22 08:30:20.110090     Dell_2b:47:ab    GOOSE     Iec-Tc57_01:00:00    173
  22 2019-01-22 08:30:20.157849     Dell_2b:47:ab    GOOSE     Iec-Tc57_01:00:00    173
  23 2019-01-22 08:30:20.220196     Dell_2b:47:ab    GOOSE     Iec-Tc57_01:00:00    174
  24 2019-01-22 08:30:20.256378     Dell_66:c8:1c    GOOSE     Iec-Tc57_01:00:00    173
  25 2019-01-22 08:30:20.258973     Dell_66:c8:1c    GOOSE     Iec-Tc57_01:00:00    173
  26 2019-01-22 08:30:20.290079     Dell_66:c8:1c    GOOSE     Iec-Tc57_01:00:00    173
  27 2019-01-22 08:30:20.330759     Dell_2b:47:ab    GOOSE     Iec-Tc57_01:00:00    174
  28 2019-01-22 08:30:20.337219     Dell_66:c8:1c    GOOSE     Iec-Tc57_01:00:00    174
```

GOOSE packet indicating Generator 78 Out of Step function Operate

GOOSE packet indicating R_{TL} direct trip

Fig. 17: GOOSE stream capture

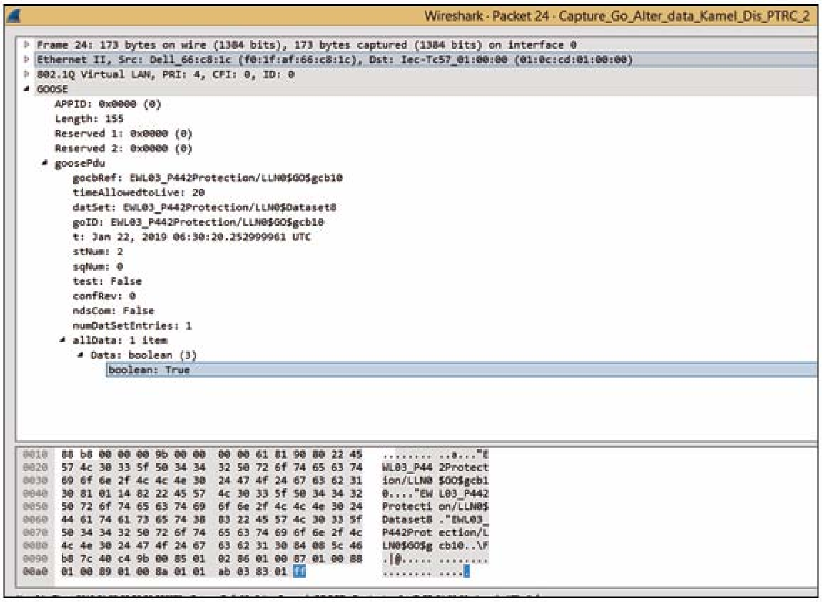
The results of this study indicate that the proposed scheme provides a smart coordination of the tripping role between Relay 78 and R_{TL} in order to maintain the synchronous operation of the local generator and prevent its tripping by Relay 78 during and after system disturbances. In this regard when a sudden load is applied at bus B in the system shown in Fig. 6 at t = 6.65 sec causing power swing oscillations, R_{TL} is blocked from operation by PSB. As a result, the pole slipping condition is initiated in the generator and then the impedance



```
▷ Frame 19: 173 bytes on wire (1384 bits), 173 bytes captured (1384 bits) on interface 0
▷ Ethernet II, Src: Dell_2b:47:ab (b8:ac:6f:2b:47:ab), Dst: Iec-Tc57_01:00:00 (01:0c:cd:01:00:00)
▷ 802.1Q Virtual LAN, PRI: 4, CFI: 0, ID: 0
◢ GOOSE
    APPID: 0x0000 (0)
    Length: 155
    Reserved 1: 0x0000 (0)
    Reserved 2: 0x0000 (0)
  ◢ goosePdu
      gocbRef: EWL03_P442Protection/LLN0$GO$gcb09
      timeAllowedtoLive: 20
      datSet: EWL03_P442Protection/LLN0$Dataset6
      goID: EWL03_P442Protection/LLN0$GO$gcb06
      t: Jan 22, 2019 06:38:16.063799977 UTC
      stNum: 6
      sqNum: 0
      test: False
      confRev: 0
      ndsCom: False
      numDatSetEntries: 1
    ◢ allData: 1 item
      ◢ Data: boolean (3)
          boolean: True
```

```
0010  88 b8 00 00 00 9b 00 00  00 00 61 81 90 80 22 45   ........ ..a..."E
0020  57 4c 30 33 5f 50 34 34  32 50 72 6f 74 65 63 74   WL03_P44 2Protect
0030  69 6f 6e 2f 4c 4c 4e 30  24 47 4f 24 67 63 62 30   ion/LLN0 $GO$gcb0
0040  39 81 01 14 82 22 45 57  4c 30 33 5f 50 34 34 32   9...."EW L03_P442
0050  50 72 6f 74 65 63 74 69  6f 6e 2f 4c 4c 4e 30 24   Protecti on/LLN0$
0060  44 61 74 61 73 65 74 36  83 22 45 57 4c 30 33 5f   Dataset6 ."EWL03_
0070  50 34 34 32 50 72 6f 74  65 63 74 69 6f 6e 2f 4c   P442Prot ection/L
0080  4c 4e 30 24 47 4f 24 67  63 62 30 36 84 08 5c 46   LN0$GO$g cb06..\F
0090  ba 58 10 55 32 00 85 01  06 86 01 00 87 01 00 88   .X.U2... ........
00a0  01 00 89 01 00 8a 01 01  ab 03 83 01 ff            ........ .....
```

Fig. 18: Relay 78 operation



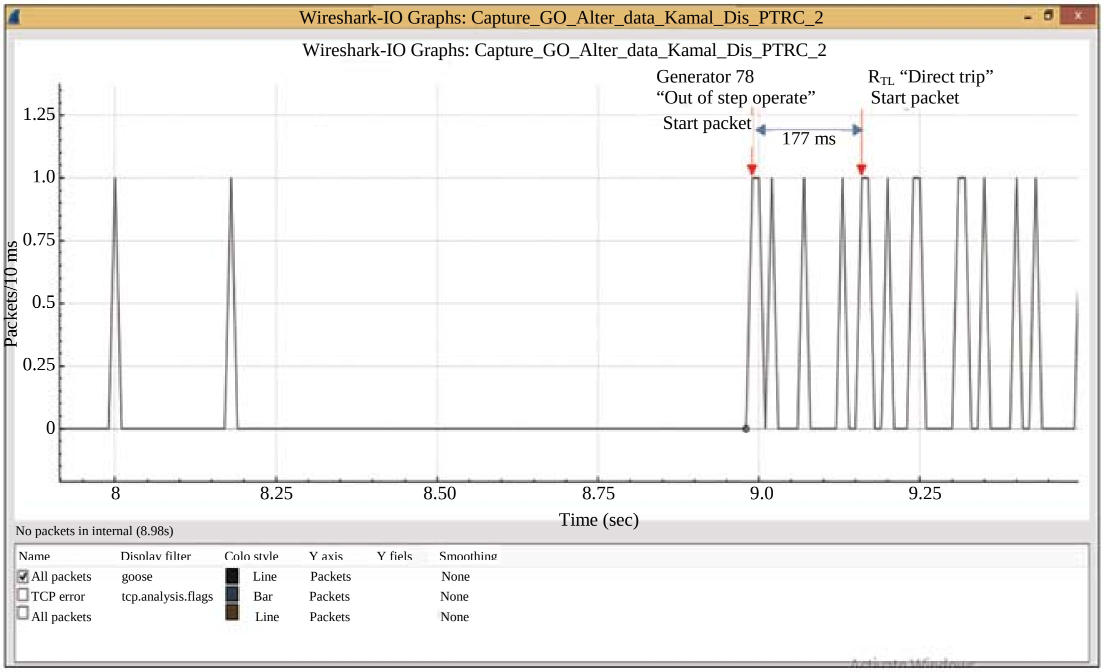
```
▷ Frame 24: 173 bytes on wire (1384 bits), 173 bytes captured (1384 bits) on interface 0
▷ Ethernet II, Src: Dell_66:c8:1c (f0:1f:af:66:c8:1c), Dst: Iec-Tc57_01:00:00 (01:0c:cd:01:00:00)
▷ 802.1Q Virtual LAN, PRI: 4, CFI: 0, ID: 0
◢ GOOSE
    APPID: 0x0000 (0)
    Length: 155
    Reserved 1: 0x0000 (0)
    Reserved 2: 0x0000 (0)
  ◢ goosePdu
      gocbRef: EWL03_P442Protection/LLN0$GO$gcb10
      timeAllowedtoLive: 20
      datSet: EWL03_P442Protection/LLN0$Dataset8
      goID: EWL03_P442Protection/LLN0$GO$gcb10
      t: Jan 22, 2019 06:30:20.252999961 UTC
      stNum: 2
      sqNum: 0
      test: False
      confRev: 0
      ndsCom: False
      numDatSetEntries: 1
    ◢ allData: 1 item
      ◢ Data: boolean (3)
          boolean: True
```

```
0010  88 b8 00 00 00 9b 00 00  00 00 61 81 90 80 22 45   ........ ..a..."E
0020  57 4c 30 33 5f 50 34 34  32 50 72 6f 74 65 63 74   WL03_P44 2Protect
0030  69 6f 6e 2f 4c 4c 4e 30  24 47 4f 24 67 63 62 31   ion/LLN0 $GO$gcb1
0040  30 81 01 14 82 22 45 57  4c 30 33 5f 50 34 34 32   0...."EW L03_P442
0050  50 72 6f 74 65 63 74 69  6f 6e 2f 4c 4c 4e 30 24   Protecti on/LLN0$
0060  44 61 74 61 73 65 74 38  83 22 45 57 4c 30 33 5f   Dataset8 ."EWL03_
0070  50 34 34 32 50 72 6f 74  65 63 74 69 6f 6e 2f 4c   P442Prot ection/L
0080  4c 4e 30 24 47 4f 24 67  63 62 31 30 84 08 5c 46   LN0$GO$g cb10..\F
0090  b8 7c 40 c4 9b 00 85 01  02 86 01 00 87 01 00 88   .|@..... ........
00a0  01 00 89 01 00 8a 01 01  ab 03 83 01 ff            ........ .....
```

Fig. 19: R_{TL} direct trip is triggered

seen by Relay 78 penetrates its characteristic and the right blinder; thus, Relay 78 picks up and sends a GOOSE message to R_{TL} simultaneously to force it trip the line suffering oscillations (unconditional tripping). This will be very useful if R_{TL} is not able to detect quickly the change from stable to unstable power swing (out of step condition), which actually happened in the studied case. As a result of tripping the line suffering oscillations, the oscillations seen by Relay 78 is disappeared and the pickup status of Relay 78 is released as the generator recovers its normal operation as shown in Fig. 10 and 11. This will enable the generator to supply other loads in the system during and after such disturbances.

This scheme has been implemented as shown in Fig. 14-19. Figure 20 shows the Initiating GOOSE packets from Relay 78 to R_{TL} during the disturbance caused by a sudden load application at bus B. R_{TL}



No packets in internal (8.98s)

Name	Display filter	Colo style		Y axis	Y fiels	Smoothing
☑ All packets	goose	■	Line	Packets		None
☐ TCP error	tcp.analysis.flags	■	Bar	Packets		None
☐ All packets		■	Line	Packets		None

Fig. 20: Initiating and triggered GOOSE packets

responds to these GOOSE packets and provides an instantaneous tripping order to the line (indicated by the triggered GOOSE) after 177 msec. This time interval represents the round trip time within R_{TL}.

The total time delay between Relay 78 and R_{TL} tripping can be divided into three intervals; the publishing time of Relay 78, the roundtrip time within R_{TL} and the network transfer time from Relay 78. This can be stated as:

$$t_{total\ delay} = t_{a\text{-}78}+t_{roundtrip}+t_b \quad (1)$$

where, $t_{a\text{-}78}$ is the publishing time of Relay 78, $t_{roundtrip}$ is the time delay between published and subscribed GOOSE within R_{TL}, t_b is the network transmission time between two IEDs. Figure 21 shows the roundtrip time as defined by IEC 61850-10 (Schimmel and Xu, 2010). This can be stated as:

$$t_{roundtrip} = t_a+t_c+t_{application} \quad (2)$$

where, t_a is the publishing time of R_{TL}, t_c is the subscription time of R_{TL} and $t_{application}$ is theinternal logic processing time of R_{TL}.

The publishing time is generally less than 1 ms. The network transmission time between two IEDs is a few microseconds (Schimmel and Xu, 2010).Thus, it can be neglected and Eq. 1 yields:

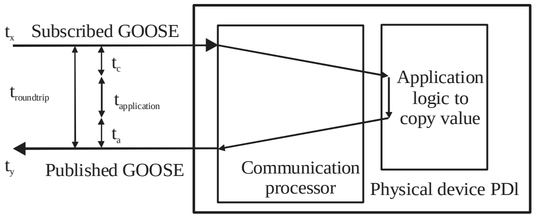


Fig. 21: Ping-Pong method for measurement the round trip time of GOOSE

$$t_{total\ delay} = t_{roundtrip}+t_{a\text{-}78} = 177 \text{ msec approximately}$$

This exhibits a long time delay, however this is due to a long logic processing time ($t_{application}$) in the simulator used in this study. This is an internal issue in the simulator that could be tackled to get it closer to the performance of real IEDs working on Real Time Operating Systems (RTOS).

CONCLUSION

In this study, the performance of the generator pole slipping protection (Relay 78) and line distance protection (R_{TL}) during a disturbance caused by a sudden large load application has been investigated. The tripping of local generator by Relay 78 instead of tripping the line suffering oscillations by R_{TL} during such disturbances has highlighted the need for intelligent communications between Relay 78 and R_{TL} to coordinate the role of tripping between them during such disturbances. This coordination enables maintaining the synchronous operation of local generator and prevents its tripping by Relay 78, while tripping the specific line suffering oscillations. Therefore, the generator is allowed to supply other loads and support the system. Accordingly, the reliability of the system is increased. An applicable IEC 61850-based protection scheme has been proposed, it uses the GOOSE messages between Relay 78 and R_{TL}. This scheme can be simply applied to the current technology of protection relays without any extra cost. Many simulations have been executed to investigate the performance of this scheme which yield acceptable results that prove the effectiveness of this scheme.

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APPENDIX

Network parameters: 220 kV±10%, 50 Hz ±2.5%, 3PH short circuit current 24.5 kA

Generator data: 437 MVA, 21 kV, power factor 0.85 lag, 0.89 lead, Xd (saturated) 176.6%, X'd (sat) 29.4%, X"d (sat) 18.8%, Xq (sat) 179.4%, X'q (sat) 45.1%, X"q (sat) 19.7%, X2 (sat) 19.2%, Xo (sat) 10.4%, stator resistance per phase at 20°C (Ra) = 0.708 mΩ, J = 8084 kg m^2, H = 0.913 sec

IEEE excitation system model (ST1A): T_r= 0.02 sec, T_a = 0.001 sec, K_a=210, VA_{min} = -15 pu, VA_{max} = 15 pu, VR_{min} = -6.0 pu, VR_{max} = 6.43 pu, K_F = 0.001, K_C = 0.038 pu, T_F = 1 sec

Generator Step Up Transformer (GSUT) data: 480 MVA, 21 kV/220 kV, Δ/Y_g, X_t= 0.15 pu.

Transmission line parameters: R_1= 0.04 Ω/km, R_o= 0.25 Ω/km, X_L = 0.3 Ω/km, C1= 2.8×10^{-8} F/km, linelength = 140 km

Transmission line distance protection relay (R_{TL}): Z1 = 33.89 Ω with no time delay. Z2 = 50.8 Ω, t_2 = 500 msec
Z3 = 65 Ω, t_3= 1 sec
VTR = 220/0.1, CTR= 1000/5, MTA = 80º

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