A Novel Method of executing Main-Tie-Main LV Secondary Selective Systems

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***Abstract* –** Large industrial facility power distribution systems are typically designed as secondary selective schemes to increase system reliability and flexibility for the operator during maintenance. Existing Main-Tie-Main protection and control schemes utilize three microprocessor-based relays for the Automatic Transfer Switching (ATS), breaker control, Human Machine Interface (HMI) and electrical system protection. One protection relay is located at each of the three Main-Tie-Main (M-T-M) breakers, each communicating with the others over fiber or copper to perform the ATS operation. This paper proposes using only one (1) microprocessor relay to control all three (3) breakers as well as perform ATS, Electrical Control and Monitoring System (ECMS) Interface and HMI. Details of a Proof-of-Concept test proving this functionality is included. This scheme reduces the quantity of microprocessor relays by two-thirds for LV Main-Tie-Main schemes. Methods of retaining protection reliability and redundancy are discussed.

Index Terms — Relay Optimization, Automatic Transfer Scheme, Main-Tie-Main, Secondary Selective Systems, Microprocessor relay testing, Solid State Trip Unit

I. INTRODUCTION

Use of microprocessor-based relays in systems for protection and control applications is commonplace. These relays support several protection functions, control applications, multiple setting groups and complex logic based on application requirements. Whereas relays may have advanced in features and capabilities, being able to apply them successfully and maintaining reliability is of importance and users can benefit from further analysis.

Per Fig 1 from the 2015 NERC report on *Analysis of System Protection Misoperations [1]*, the top three causes for power system mis-operations are:

1) Incorrect setting/logic/design errors - 31%
2) Relay failures/malfunctions – 18%
3) Communication failures. – 13%.

One of the recommendations from this report to address design and logic issues is to use standard templates for setting standard schemes using complex relays [1]. The Authors agree with this recommendation and proposed the scheme in this paper as the most scalable design for implementation on all Low Voltage M-T-M switchgear irrespective of transformer size. In Industrial projects, low voltage switchgear quantity is much greater when compared to Medium Voltage Switchgear. However, any design template that can be implemented without modifications on a large scale helps improve system reliability, performance predictability, ease of maintenance and testing, and reduces overall cost. The scheme proposed in this paper is described in terms of LV systems, but it is scalable to larger MV systems for ease and consistency of implementation at industrial sites.

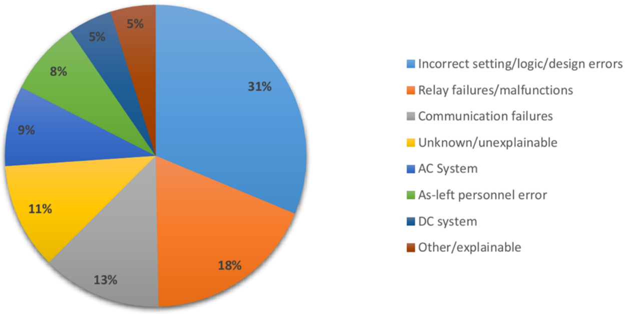

Fig. 1- Misoperations by cause code from 2013-2014 [1, NERC 2015]

Section II of this paper will describe traditional dead-bus ATS schemes, which are executed over three (3) multi-function relays on industrial projects. Section III of the paper details the Authors' proposal for optimization of LV secondary selective scheme at M-T-M using a single relay. Furthermore, use of Solid-State Trip Units at each breaker to maintain protection reliability and eliminate single-point-of-failure is included. Section IV describes how a proof-of-concept test of the proposed scheme was conducted for demonstration prior to large scale implementation. Section V details commissioning and testing recommendations for this scheme. Section VI Compares the traditional ATS scheme to the Authors' scheme for application suitability. Section VII summarizes the paper.

II. TRADITIONAL MAIN-TIE-MAIN SCHEME

A. *Secondary Selective Scheme*

Power distribution systems for industrial facilities typically employ secondary selective schemes which utilize two (2) main incoming breakers and one (1) tie breaker, often referred to as the Main-Tie-Main (M-T-M). M-T-M schemes are designed with an Automatic Transfer Scheme (ATS) that allows for transfer of loads from one source to the other in the event of a line side fault or transfer trip. M-T-M are also equipped with a Manual Transfer Scheme (MTS) in the event of an operation or maintenance requirement for seamless source transfer.

Existing industry practice is to implement three relays or Intelligent Electronic Devices (IEDs), one at each breaker, for protection, control and ATS/MTS functionality implemented over GOOSE (Generic Object-Oriented System Event) or IEC 61850. Figure 2 below shows a typical LV secondary selective scheme [3].

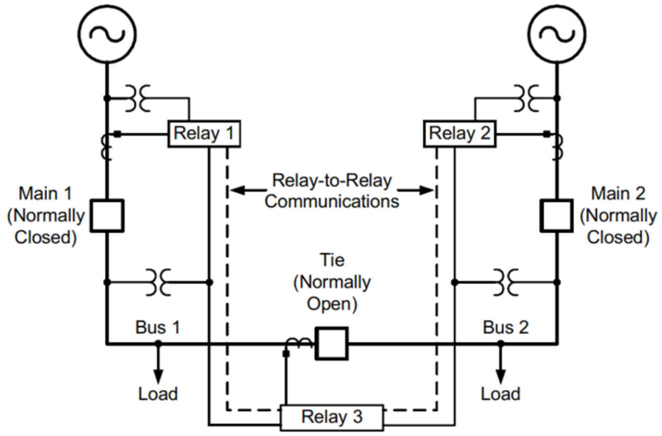

Fig. 2 Traditional Main-Tie-Main Scheme [3]

Following are observed and noted regarding this scheme:

1) Protection: Each relay protects the breaker it is associated with. Typical protection functions required for LV Main breakers are:

a) An Inverse Time Over Current function (51) with a definite time function (50TD). This function would trip a breaker in the event of an overcurrent exceeding pre-set magnitude of fault current and duration set in the relay. Any bus overcurrent fault detected at the main breaker blocks the ATS scheme from operating, thus preventing closing into a fault.

b) Ground fault protection is required in case the LV system is low resistance grounded or solidly grounded. For the purposes of this paper, the LV system is assumed to be High Resistance Grounded (HRG). An HRG system allows the system to continue operating after one single-line-to-ground fault. Results and recommendation of this paper remain the same regardless of system grounding.

c) 27 Undervoltage is required for ATS functionality. This function confirms dead bus or a voltage lower than residual voltage prior to transfer of power to secondary source.

d) Trip Coil Monitoring: In the traditional scheme, each relay monitors the trip coil of the breaker it controls. In the event a trip coil is bad, breaker closing can be blocked to avoid operating a system without proper means of isolation for protection.

2) *Control*: Multi-function relays are also used for control of the circuit breaker from either in front of the switchgear or from a remote-control station over fiber or copper.

a) Each relay has a separate Local/Remote (L/R) Switch, the status of which is an input the relay logic in determining method of control: whether the breaker is being controlled from the front of the switchgear (local mode), or by a remote user in a separate control room (remote mode). It is important for the operating procedures to account for status of all L/R switches that need to be set/reset when working on the switchgear. For example, when working on the bus side of Bus A, it may be advisable to set both Main A and Tie breaker relays in "Local" mode to avoid operation of either breaker from "Remote" while maintenance work or troubleshooting is on-going. A traditional M-T-M scheme has (3) L/R switches – one for each breaker. External L/R switches can be of the pistol-grip type or selector switch type. Relays can be equipped with a built-in L/R switch as well.

b) MTS Selector Switch: This switch is used for Manual Transfer Schemes to allow closing a breaker and tripping a closed breaker in a make before break sequence. MTS switch logic is generally implemented in the Tie Breaker relay. MTS switch is also used for bringing the system back into normal configuration after the ATS scheme has operated and the system normal conditions have been restored.

c) 52CS Switch: The 52CS, breaker control switch is a pistol-grip switch that is utilized occasionally depending on operator preference for breaker control.

d) Sync Check (25) function for each breaker is performed in the relay that controls the breaker. Sync Check function verifies voltage and frequency of the system are within specified limits to allow breaker closing. Typical relays used on LV schemes have only (4) four PT input where usually (3) PT input is used for three phase line voltage measurement and (1) PT is used for sync check input from bus PT.

3) Communication: Each relay communicates relevant information associated with the breaker for remote monitoring and control typically referred to as the Electrical Control and Monitoring System (ECMS). Alternative names such as Power Management System (PMS), SCADA (Supervisory Control and Data Acquisition), Electrical Network Monitoring and Control System (ENCMS) are also used. For the purposes of this paper, the term ECMS shall be used. Each relay records analog and digital data. Analog data may include magnitude, phase angle, or even complete waveform of current or voltage; digital data may include breaker status and position, Local/Remote Switch position, and Lock-out Relay status (86). This information is transmitted over the network to the Central Control Room where the entire system's data can be collected, monitored, and analyzed. Control commands can be sent to the relay over this network. The application engineer can select required network topology based on desired redundancy and availability of communication ports in the relay. A relay with dual communication ports helps maintain redundancy and reliability in maintaining system response time and transfer of information.

4) HMI: Most microprocessor-based relays are generally equipped with LED screens that can be used as an HMI. In the traditional three relay scheme, each relay's LED screen mimics the one-line for the specific breaker it protects. Circuit Breaker open/close status, circuit breaker truck position in test/service condition can be programmed on the HMI. In addition, analog data such as voltage and current can be displayed. See Figure 3 for a sample LV relay HMI.

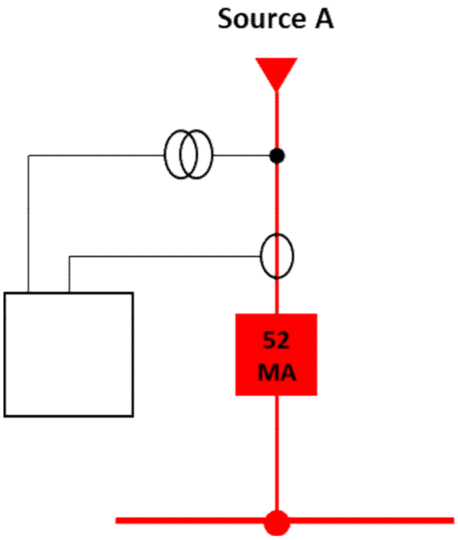

Fig. 3 Sample Main Relay HMI

5) Metering: Multi-function relays are used as metering devices to display and transmit measured currents and voltages. Derived information based on these inputs such as real power, apparent power, power factor, symmetrical components etc. are generally available as well.

6) Interlock / Transfer trip: Interlocks/transfer trip between Medium Voltage (MV) transformer feeder and Low Voltage (LV) Main breaker can be implemented as a hardwired scheme, over fiber or a combination of the two. When MV Switchgear feeder and LV Switchgear mains are within the same substation or within short distance, interlock/transfer trip scheme can be hardwired directly on the breaker closing and trip coils. A Dedicated communication link for protection signals can be used based on the relay model used. GOOSE with 100% network redundancy can also be utilized for protection and communication purposes, especially in cases where the MV Switchgear Feeder and LV SWGR have long distances between them.

B. Traditional Three-Relay Scheme Logic

Fig. 4 shows a sample one-line diagram used for implementing the ATS/MTS scheme over the three relays. This traditional scheme has been written about and been in use in the industry for over a decade. This paper will not go into details of relay logic and explanation of the traditional scheme. Ref 2 and Ref 4 are papers the reader can refer to on this scheme and work done by other authors in the area.

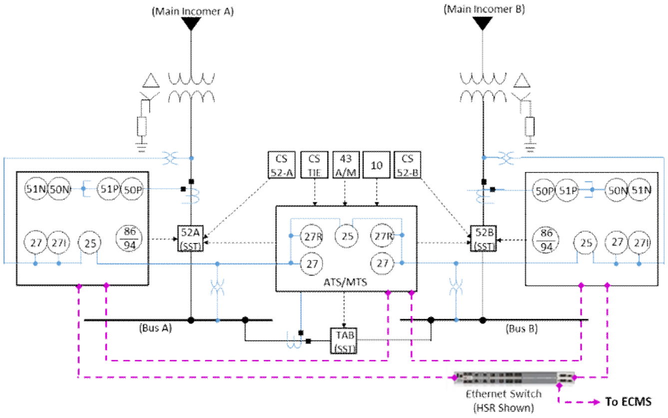

Fig. 4 Three Relay ATS/MTS Scheme

III. OPTIMIZED SCHEME

A. Optimized Secondary Selective Scheme

Today's more powerful and sophisticated microprocessor relays have advanced capabilities including analog and binary input/output cards, large HMI screens and fully configurable logic. This additional flexibility can be used to optimize existing protection and control schemes and simplify the user interface. Fig 5 shows a one-line drawing of the proposed LV secondary selective optimized scheme.

This LV ATS/MTS scheme performs the same function as the (3) Relay ATS/MTS scheme described in the previous section. In the event of a line-side fault on A or B side, the corresponding main breaker trips, and the tie breaker closes after a set time delay to serve loads when the other main breaker side is healthy.

This scheme includes a circuit breaker selector switch, identical to the previous scheme, for manual transfer of loads during maintenance activities and for re-transfer to normal configuration after power system conditions have been restored to normal.

The time-delay in operation of the ATS system ensures voltage on the side that is isolated is below residual voltage. Closing into a bus while residual voltage is high could result in damage to rotating equipment.

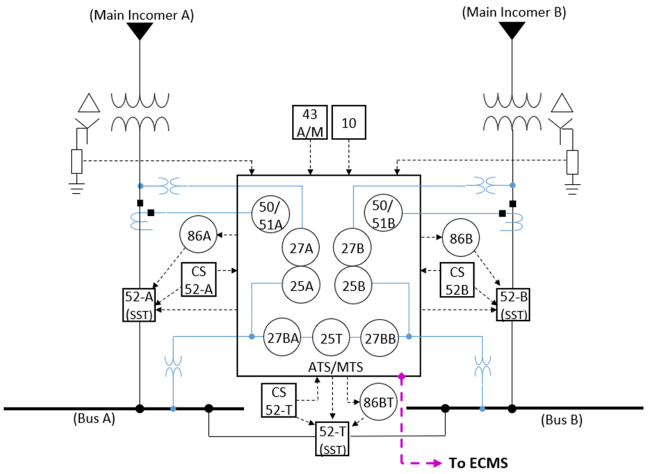

Fig. 5 Optimized ATS/MTS LV Scheme

Following are observed and noted regarding this scheme:

1) *Protection:* Each relay protects the breaker it is associated with. Typical protection functions required for LV Main breakers are:

   a) Phase Overcurrent Protection:
      - i) In case of the optimized relay scheme, LV Solid State Trip (SST) units with Long time, Short time & Instantaneous (LSI) function are utilized.
      - ii) LSI trip units are simpler to program, commission and test. Their trip time is faster when compared to the total trip time of a relay operation and an air circuit breaker opening time.
      - iii) For LV Mains where fault currents are usually much higher, faster trip time of an LSI unit reduces arc-flash incident energy experienced at the main breaker.
      - iv) Use of an SST unit allows for system protection to remain independent of ATS/MTS operation, thus eliminating any likelihood of a single point of failure.
      - v) If desired, the single relay can be programmed for back up overcurrent protection for both mains. This allows for increased protection reliability and safety.

   b) Ground fault protection: As mentioned earlier, ground fault protection is required in case the LV system is low resistance grounded or solidly grounded. If the LV system does require ground fault protection, the SST unit can be LSIG type where G stands for ground fault protection. As shown in the one-line drawing, LV system in this case is High Resistance Grounded (HRG).

   c) Undervoltage function: The single relay IED is programmed for 27 Undervoltage function for both mains as input to the ATS logic.

   d) Sync Check (25) function for each breaker is performed in the same relay.

   e) Trip Coil Monitoring: Newer microprocessor relays are capable of monitoring trip coils for multiple breakers with separate indication for each.

   f) Analog Inputs: When implementing the Optimized relay scheme, it is important to verify the number of analog inputs – Current input and voltage input channels the relay can support. As seen in blue font in Figure 5 the relay should be able to support a minimum of following analog inputs:
      - i) Two (2) Three-phase CT inputs,
      - ii) Two (2) Three-phase PT inputs and
      - iii) Two (2) One-phase PT input for Synch checks.

   g) Binary Inputs/Binary Outputs (BI/BO): Often, during project execution, relay logic flexibility is limited by its BI/BO limitation on the chassis. On such occasion, auxiliary relays outside of the IED are sometimes utilized. The following should be considered prior to selection of the IED to ensure the optimized scheme can be successfully implemented:
      - i) Circuit breaker status contacts for each of the three breakers – Open/close, service/test etc.
      - ii) LSI trip indication, HRG alarm and any other alarm contact input needed for status transfer to control room.
      - iii) LOR (86) status contacts
      - iv) Transformer alarm/trip indication contacts.
      - v) 52CS, L/R switch and other external device status contacts.
      - vi) BO to support Open, closing, tripping of each of the three breakers.
      - vii) Having spare BI/BO for design development are recommended and is generally good practice for successful project execution.

2) *Control*:

   a) With the traditional ATS scheme using three relays,(3) Local/Remote Switches were used. Each relay had a separate L/R Switch, the status of which is an input in the relay logic in determining method of control. In the proposed scheme, a single L/R switch is required.

   b) In the optimized scheme when the L/R switch is in “Local” mode, all three breakers on the LV Switchgear can be controlled by the User at the switchgear. When the L/R switch is in “Remote” mode, all three breakers are in control of the control room operator.

c) Operation of breaker selector switch for MTS scheme and 52CS switch for breaker open/close remain un-changed.

3) *Communication*: In the optimized relay scheme, one relay with dual communication ports communicates with the central control room in a star topology. The control room operator can monitor all three breakers via the same IED and send open/close commands for required breaker. Breaker Identification is generally intuitive to avoid human error in operation of an incorrect breaker. This recommendation is true for both the “three relay” scheme as well as the “one relay” optimized scheme.

4) HMI: Newer microprocessor-based relays can be equipped with large LED screens, touch-screen capability, and colorful, customizable graphics making it easy to maneuver through the relay and monitor existing switching positions. See Figure 6 for a sample LV relay HMI display. This LED screen HMI mimics the one-line for all three M-T-M breakers on one screen. Since protection function in the proposed scheme is implemented using SSTs, alarm/trip status signals from each SST are wired to the IED for indication and remote monitoring. This includes SST trip, transformer trip, HRG alarm, LOR (86) status, circuit breaker open/close status, truck position in test/service etc. Another page is available for metering values. This intuitive and user-friendly interface makes it easy for the end-user to safely work on the switchgear while monitoring a single screen for all three breakers.

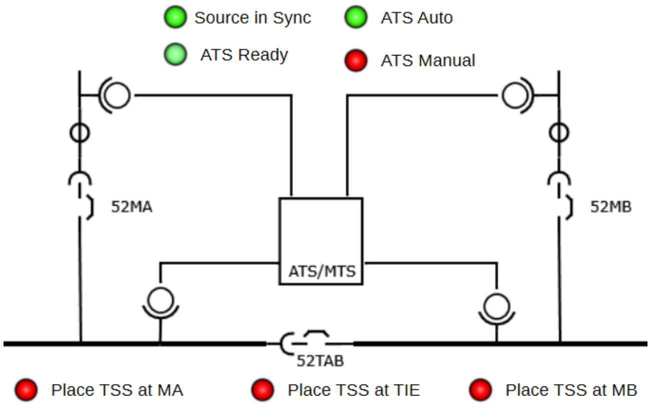

Fig. 6 Sample Optimized Scheme Relay HMI Display

5) Metering: Optimized relay scheme with CT and PT inputs as shown in the one-line drawing in Fig 5 is capable of measuring current, power and calculate system real and reactive powers, power factor, symmetrical components, and fault monitoring. The relay can be configured to trigger fault recording for events on either or both incoming lines and bus.

6) *Interlock / Transfer trip:* With the proposed scheme, hard-wired interlock/transfer trip scheme remains unchanged. In the event that interlocks/transfer trips over communication are desired, GOOSE with dual communication and 100 percent network redundancy can be utilized.

IV. RELAY PROOF OF CONCEPT TESTING

Before considering a significant change in design that will be scaled on the project, it is advisable to conduct a proof-of-concept test for (1) testing and verifying the design, (2) vetting out any operating scenarios the design may have missed, and (3) demonstration to and training of personnel that may not be familiar with use of relays and IEDs. Proof-of-concept testing is a low-cost investment that gives everyone involved the benefit of understanding the scheme and confidence in the design thus leading to scalability.

Advantages of Proof-of-Concept Test are:

1. Required Analog Input/Output sufficiency can be verified.
2. Required number of Binary Input/Output for intended design can be verified.
3. Operational logic can be tested and verified with the Client.
4. Any special scenarios that the operator or maintenance crew might go through can be simulated. Any project procedures that need to be developed can identified and simulated.
5. Decision on programming of target LEDs, HMI screen and signal transfer to ECMS can be made with Client approval during early stages of the project making execution simpler.
6. Switchgear Factory Acceptance Test (FAT), substation Integrated Factory Acceptance Test (IFAT) testing scope can be developed with focus on external interface that was not available during proof-of-concept testing.
7. Test set up can be retained through the life of the project for demonstration, design review and trouble-shooting assistance to the field from the office.

Fig 7 shows a picture of the test rack developed for testing the optimized relay scheme. It consists of test switches for analog input simulation, relay, (3) LV circuit breaker simulators to simulate breaker positions, breaker selector switches, L/R switch and TSS (trip selector switch) etc.

Fig. 7 Proof of Concept Test Cabinet

Table I shows a sample checklist that can be developed prior to the test to run thru different system scenarios for logic testing. This checklist helps ensure all possible logic conditions can be checked. Operational and maintenance conditions can be simulated as well. The more deliberate, detailed, and exhaustive the checklist scenarios can be, the better it is for the design and project execution. All important decisions that impact implementation can be discussed and agreed early on.

It should be noted however, that a proof-of-concept does not guarantee a problem-free execution phase. Since external interfaces of the relay are all simulated, attention should be paid during detailed design drawing reviews, factory acceptance testing, integrated substation/jobsite commissioning and testing where the system is integrated together. Each interface point should be tested and verified for complete overall functional testing of the system.

As seen in TABLE I, expected outcome is listed in detail to make sure complete operation of the system and logic is understood and as expected. The Authors recommend developing a test sheet for eachtypical design per project to take into account project specific requirements and end-user preferences.

TABLE I
SAMPLE CHECKSHEET FOR RELAY PROOF OF CONCEPT TEST*

#	Condition	Action	Expected Outcome	Pass/ Fail
1	MA, MB Closed - TIE Open	Enable 86TA Loss of source A	- Trip MA - Close TIE by ATS - Block re-closing of MA	
2	MA, MB Closed - TIE Open	Enable 86TB Loss of source B	-Trip MB - Close TIE by ATS - Block re-closing of MB	
3	MA, MB Closed - TIE Open	Enable 86A	-Trip MA - Block re-energization of Bus A	
4	MA, MB Closed - TIE Open	Enable 86B	-Trip MB - Block re-energization of Bus B	
5	TIE, MA Closed - MB Open	Enable 86BT	-Trip TIE - Block re-closing of TIE	
6	MA, MB Closed - TIE Open	Simultaneous loss of sources A and B	- Open both MA and MB - TIE remains open	

**Actual test scenario would have considerably more scenarios*

V. COMMISSIONING AND TESTING

Testing and commissioning of multifunction relays, employed in a Main-Tie-Main configuration and utilized for ATS, require testing of both the individual relay and associated inputs as well as testing of the three relays interaction with each other to perform the ATS operation. This testing can be complex and time consuming as it requires testing of the individual inputs to each relay as well as testing the relay communication between them. For the traditional three relay scheme used for ATS, the testing typically involves a systematic approach to testing each relay and includes the following:

1) Injection of current and voltage into the relay to verify relay setting and timing
2) Verify proper relay input and output
3) Verify proper relay logic
4) Verify tripping and targets.

The amount of time required to perform all testing activities on a per-relay basis can vary based on the testing equipment used, the availaby of test switches for secondary injection, and the quantity of BI/BO's being used. When testing a three-relay scheme, the process must be performed for each relay location and includes the time required for moving, connecting, and disconnecting the test set at each location. When compared to the testing required for a single relay used for the ATS, there is a significant amount of time saved because of not having to disconnect and move the test set and re-perform testing for the additional two relays. Furthermore, with the ATS functionality limited to a single device, the additional testing to verify relay-to-relay communication is not required.

Utilizing a standardized relay settings template for typical designs is one way to ensure that relay settings are consistent across a large project. The template should limit those user settable parameters to the bare minimum such that those which can remain as default from the manufacturer are not available for the user to make a change. When combined with the proof-of-concept test to verify the logic, the standardize relay settings can result in time savings in site testing activities and allow scalability of settings across the project.

VI. COMPARISON BASED ON A PROJECT

The proposed single IED scheme is compared with the traditional three IED scheme using a two-train LNG project.

1. Current Transformers – (2) Main incoming phase CTs, and a bus tie CT. Since there are only two sources of power and their analog input go into the same relay, a tie CT is not required in the optimized scheme.
2. Three relays (IEDs) are used in the traditional scheme and are communicating with CCB (Central Control Building) via a ring configuration. In the Optimized scheme, the single IED is communicating in a star configuration with 100 percent network redundancy.
3. Three L/R switches, one for each relay for control of each breaker where only one L/R switch is required in the new scheme.
4. The quantity of relays reduced by 2/3rd from 90 to 30.
5. The amount of time required in programming. The amount of time required for programming can vary depending on complexity of logic or software utilized for relay programming. The numbers shown in Fig 9 are to demonstrate the order of magnitude comparison.
6. Testing and commissioning of the system is reduced, since the logic is identical for all LV systems, irrespective of the transformer size.
7. Since the number of IEDs are significantly reduced, the ECMS network architecture is simplified.
8. The quantity of fiber inside the substation is reduced for the optimized scheme.
9. The optimized scheme requires less wiring inside the switchgear.
10. Flexibility of ATS/MTS scheme throughout the life of the project. In the traditional scheme, modification to the ATS scheme could require additional wiring to the tie relay, or programming changes on all three relays. The optimized scheme avoids such changes by including all status signals and output in one relay.
11. In the event the single optimized relay is lost, system operation continues as-is. Protection remains intact with the use of SSTs. Loss of the optimized relay in terms of system design is similar to loss of the tie breaker relay in the traditional design. Thus, system reliability remains the same.
12. ATS scheme and SST units can be factory tested prior to shipment thus reducing time required at site for commissioning and testing of LV Switchgear and relays.

Table II shows the difference in equipment count between the traditional "old" three relay scheme vs the Authors' proposed optimized "new" scheme. In the Optimized relay scheme, the CTs, L/R switches and IED count is reduced. Data is represented using a project with 30 LV switchgear as basis. Project specific impact should be evaluated.

TABLE II
COMPARISON OF THREE RELAY & ONE RELAY SCHEME - EQUIPMENT

		Per LV SWGR		Across project	
#	**Description**	**OLD**	**NEW**	**OLD**	**NEW**
1	(3) Phase CTs	3	2	90	60
2	L/R Switches	3	1	90	30
3	Total IED Count	3	1	90	30

*Using 30 LV switchgear project for comparison

Table III shows the relative change in percentage of testing scope as compared between the traditional "old" three relay scheme vs the Authors' proposed optimized "new" scheme.

Figure 9 below is a visual representation of the data in Table III. Overall testing time and scope on the project is reduced. Project specific saving should be evaluated based on complexity of logic and testing scope.

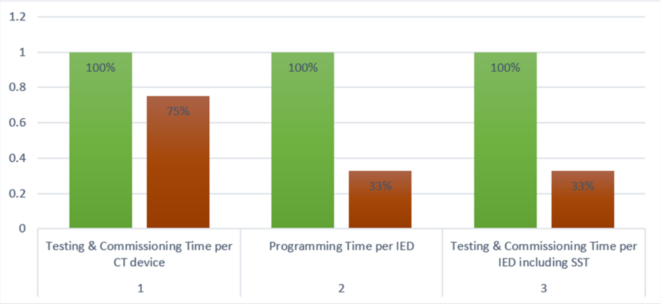

Fig. 9 "Three relay" scheme vs "One relay" scheme – Testing

VII. CONCLUSIONS

Power System distribution schemes for large industrial projects are designed based on project requirements, client preferences and philosophy of operation. This paper proposed an optimized relay scheme for LV secondary selective schemes for consideration in future projects. Comparison between existing LV ATS/MTS schemes with the proposed scheme has been provided to show the benefits of the new scheme. Further work in this area could include utilization of a proposed scheme in a 100 percent redundant application and MV Switchgear M-T-M applications.

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IX. VITAE

Gautami Bhatt received her B.Tech from the Jawaharlal Nehru Technological University in 2009 and M.E.E from the University of Houston in 2010. In 2011 she joined Bechtel Energy Inc. and has worked on LNG and Petrochemical projects as a Senior Electrical Engineer in design office for 9 years and as a Startup and Commissioning System Specialist since August 2020. She is a senior member of the IEEE and serves as the Chair for the IEEE Industry Applications Society Houston Section. She is a registered Professional Engineer in the state of Texas.

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Vincent Duong currently holds a Digital System Architecture Manager position in the Digital System Solutions group at ABB. He received his BSEE degree with Power System Specialization from the University of Alberta in Edmonton, Canada; and both MBA and MS in Operations and Project Management degrees from Southern New Hampshire University in Manchester, New Hampshire. Vincent has spent most of his career in distribution and transmission protection, controls, and automation engineering, including system modeling, study, design, relay settings, and system disturbance analysis. He is also actively involved in customer training and power system protection-coordination instruction. He is an IEEE member, a registered Professional Engineer of New Hampshire, and Project Management Professional of Project Management Institute (PMI).