ETAP Simulations of Adaptive Overcurrent Protection Scheme for Distribution Network with Microgrids

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Keywords: Microgrids, Distributed Generation, Adaptive over Current Protection, Protection Coordination, ETAP.

Abstract: A microgrid (MG) includes Distributed Energy Resources (DER), controllable load with adequate protection scheme in an Electrical Power Distribution System. Renewable energy sources (RES) is expected to provide efficient, low cost and clean energy with decentralized generation, storage and local consumption with MG. In this paper an Adaptive Over Current Relays (AOCR) scheme in distribution networks (DN) considering intermittency of Distributed Generation (DG) operations using a fuzzy logic controller (FLC) is proposed. The onsite study included actual verification of protection scheme, the impact of DG on protection system and protection coordination. A part of the IEEE 44 nodes radial distribution test feeder is taken for modelling & simulating the proposed AOCR using Electrical Transient Analyzer Program (ETAP) software environment.

1 INTRODUCTION

1.1 Background

Distributed generation can be defined as "small-scale generating units located close to the loads that are being served" [Nadarajah et.al, 2017]. Given the business, regulatory and policy push, decreasing product prices, the penetration level of DG will consistently increase [Romero, 2017]. The benefits shall include: network reliability & resilience, reduction of grid congestion and peak loads, improve the operation and stability of regional grids, transmission loss & generation cost reduction, postponement of investments in network expansion, and lowering capital investment costs [Nascimento et.al, 2016]. 3 types of microgrids are; remote, grid connected and networked.

1.2 Challenges of MG Protection

Integrating DG causes the existing DN to lose its radial power flow and traditional relay settings may work incorrectly and become inadequate. Issues such as: increase in shortcircuit level, bidirectional power flow, voltage & frequency fluctuation etc. affect the protective relays performance and power quality issues [Bhise et.al, 2017]. Some of the consequences are like false tripping, under and overreach, blinding of relays and islanding [Tian et.al, 2016] require fast & accurate OC and Earth fault Protective schemes.

1.3 Proposed Solution under Study

Several schemes have been introduced to alleviate the impact of integrating DG in DNs [Saad et.al, 2017], the best being adaptive protection scheme (APS). For this project, an APS based on FLC is proposed.

2 LITERATURE REVIEW

2.1 Power System Protection

"The objective of electrical system protection and

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Palayil, P., Desai, I. and Mangroliya, D.
ETAP Simulations of Adaptive Overcurrent Protection Scheme for Distribution Network with Microgrids.
DOI: 10.5220/0011073700003203
In *Proceedings of the 11th International Conference on Smart Cities and Green ICT Systems (SMARTGREENS 2022)*, pages 130-138
ISBN: 978-989-758-572-2; ISSN: 2184-4968

coordination are to;
- Limit the extend and duration of service interruption whenever equipment failure, human error or adverse natural events occur on any portion of the system
-Minimize damage to the system components involved in the failure" (IEEE 242-2001)

Rapid disconnection of faulted apparatus limits the amount of damage to it and prevents the effects of fault from spreading into the system (Juan et.al, 2011). It can be classified into apparatus protection and system protection. ANSI numbers, according to their functions also classifies them.

2.2 Over Current and Earth Fault Relays

Overcurrent relays are classified as follow:
1. **Instantaneous Overcurrent Relays**:
2. **Definite Time Overcurrent Relays:**
3. **Inverse Time Overcurrent Relays (IDMT)**: There are several types of inverse-time curves, which are mathematically modeled under the IEC, ANSI/IEEE standards and manufacturer policies as;

$$t = \frac{TMS \times \beta}{\left({}^{I}/_{I_s}\right)^{\alpha} - 1} + L \qquad (1)$$

where: t is the operating time in seconds,
I is the fault current level at the secondary side of current transformer,
I_s is the current setting expressed at the secondary side of current transformer
L, α, β, are constants are as in Table 1.

Table 1: IEC Constants.

IEC constants for overcurrent relays

Curve Description	Standard	α	β	L
Standard inverse	IEC	0.02	0.14	0
Very inverse	IEC	1	0.0515	0
Extremely inverse	IEC	2	80	0
Long-time inverse	UK	1	120	0

Time Current Characteristics (TCC)- "Selectively coordinated" back up relay will wait for primary devices "should" sense, operate and clear the fault.

Buff Book (IEEE 242-2001)- Minimum CTIs[a]

Table 2: Minimum CTI's.

Downstream	Upstream			
	Fuse	Low-voltage Breaker	Electro-mechanical Relay	Static Relay
Fuse	CS[b,c]	CS	0.22s	0.12s
Low-voltage circuit breaker	CS[c]	CS	0.22s	0.12s
Electromechanical relay (5 cycles)	0.20s	0.20s	0.30s	0.20s
Static Relay (5 cycles)	0.20s	0.20s	0.30s	0.20s

[a]Relay settings assumed to be field-tested and calibrated.
[b]CS – Clear space between curves with upstream minimum-melting curve adjusted for pre-load.
[c]Some manufacturers may also recommend a safety factor. Consult manufacturers' time-current curves.

4. **Directional Overcurrent Relays (DOCR):** Three conditions must be satisfied for its operation: current magnitude, time delay and directionality (Bayliss et.al, 2007).

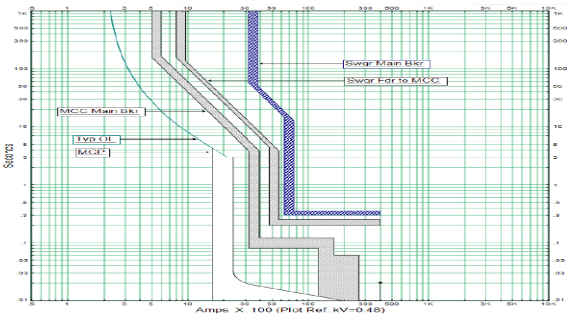


Figure 1: TCC.

2.3 Setting of over Current Relays

Based on system requirements, the pickup current of the relay is adjusted by plug bridge for required number of tapping in the coil with equation:

$$Current\ Setting = \frac{Pickup\ Current}{Ratted\ Secondary\ Current\ of\ CT} \times 100\% \qquad (2)$$

2.4 Coordination of Overcurrent Relays

Selective coordination of protective devices needed so that the fundamental protective functions are met under the required attributes of protective relaying, which are sensitivity, selectivity, reliability, and speed (Ibrahim et.al, 2016).

In numerical relays there is no overrun, and therefore the CTI can be as low as 0.2 s (Shih et.al, 2016).

Unlike the Over Current Relays, the Earth Fault relays do not respond to the 3 phase or L-L Faults. One earth fault relay is adequate to provide protection for all types of earth faults. To provide sensitive protection, it use zero sequence current and it is mandatory to keep the pick-up current (min 15%) above the maximum unbalance factor of 10%. To do setting and coordination, only L-G faults are considered.

Logic Coordination methods uses modern relays and fast communication channels, the relay setting and coordination involves primarily following steps:

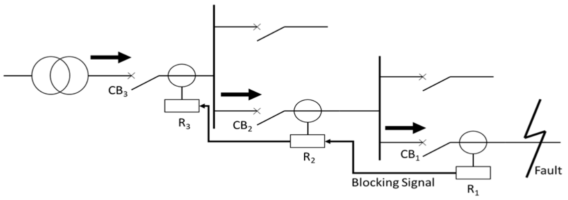


Figure 2: Logic coordination.

a) Identify all possible primary-backup relay pairs.
b) Decide the correct sequence of relay coordination.
c) Decide the pickup value and hence PSM for relays.
d) Compute the TMS to meet the coordination.
e) Validation of the results.

2.5 Steps for Coordination Study

A) Develop a SLD of the system under study.
B) Determine normal, emergency and temporary operating configurations of the system
C) Carry out the load flow analysis to determine the minimum pick up settings of various devices
D) Carry out the short circuit analysis to determine;
1.Maximum and Minimum momentary single phase and 3 phase short circuit currents
2. Maximum and Minimum interrupting duty 3 phase short circuit currents
3. Maximum and Minimum ground fault currents
E) Collect the characteristics of the devices: TCC curves & settings range from manufacturers.
F) Collect the thermal limit curves for devices
G) Determine the range of adjustments on the settings of upstream or downstream overcurrent relays.

2.6 Impact of DG Integration on Protection Coordination

MG changes the original DN topology, fault current & bidirectional flow of currents depends on fault location, capacity and number of DGs.

False Tripping and Loss of Coordination.

The definition of protection coordination loss can be taken as "violation of CTI constraint between the primary and backup relays" (Shih et.al, 2017).

Protection Blinding. Also known as protection under- reach since the actual reach of the feeder relay is decreased due to fault current contribution from the DG (Korres et.al, 2016).

Nuisance Tripping of Feeder.

Islanding Operation.

2.7 Adaptive Protection Coordination Scheme

In APS, continuous monitoring of operational and topological changes of the network is ensured. Communication has a major role in an adaptive relaying (Wan et.al, 2010). Modern relays can switch between multiple groups of time current characteristic curves based on the system operating conditions. The non-communication based APS relays respond immediately based on pre-calculated settings configured in it against different DN network topology.

2.8 Fuzzy Logic Control

It provides an inference structure as means for converting linguistic strategy into control actions and thus offers a high-level computation (Sivanandan et.al, 2007). FLC belongs to the class of "intelligent control," which uses knowledge-based decision-making employing techniques of fuzzy logic (Karray et.al, 2004) for the control actions.

There are three commonly used types of fuzzy system (Altas, 2017),

a) Mamdani fuzzy system
b) Takagi-Sugeno (TKS) fuzzy system
c) Tsukamoto fuzzy system

A zero-order Sugeno fuzzy model is functionally equivalent to a radial basis function network under certain minor constraints.

The use of FLC has increased rapidly in power systems for load/frequency control, bus bar voltage regulation, stability, load estimation, power flow analysis, parameter estimation, protection systems and many other fields.

2.9 Review on Techniques Used to Mitigate the Impact of DG Penetration on Protection Relays Coordination

Various solutions proposed are;

- Disconnecting the DGs immediately after fault detection by S. Conti, 2009
- Limiting the capacity of installed DGs (Chaitusaney et.al, 2008)
- Modifying the protection system by installing non-communication-based approach by adding more protective devices like multi-function devices & reclosers (Hamed Funmilayo and K. L. Butler-Purry, 2009).
- Installing the fault current limiters (FCLs) to

preserve or restore the original relay settings (Kim & Elmitwally et.al, 2016).

- Employing fault ride through control strategy of inverter based DGs (Naderi et.al, 2017)
- To avoid miscoordination of IDMT relays for synchronous-DG, W. Xu et.al, 2014 used a solid-state-switch-based field discharge circuit to limit the generator's fault current.
- Abbas Esmaeili et.al. 2016 used optimal programming of fault current limiters using two-stage stochastic model.
- E. Ebrahimi et al, 2014 used fault ride through approach for IBDG; Control strategy was proposed and applied to the voltage source converter (VSC) so that the protection coordination remains unchanged.
- R. Sitharthan et.al, 2016 used an APS for MG by utilizing microprocessor-based over current relays. They also used auto reclosers, through which the proposed APS recovers faster from the fault and increase the consistency of the MG as result.
- Rahmati and Dimassi, 2014 proposed an APS that uses a least square algorithm to determine the Thevenin circuit equivalent using local measurements in off-line information regarding varying short-circuit levels caused by DER infeed.

APS using differential evolution algorithm (DE) on DOCR & ABC algorithm coordination used automatic online re-adjustment of settings for different MG topologies results from dispatch or natural conditions.

Data mining and analytics or "Big Data" can play a vital role in modern MG. Main areas of Computational Intelligence (CI) methods, ANN's, PSO algorithms etc. can be used for AP Solutions. FLCs allows larger solution space and find applications in areas that derive inferences from uncertain and undefined data of renewable energy based DGs (Sampath, 2015).

3 METHODOLOGY

3.1 APS based on Pre-calculated Settings

The AOCR can be programmed for simulation with Automatic setting groups (SG) design. By auto selecting the mode of operations, with proper protection and restoration control logic the MG switchgears can be controlled automatically. Through the Etap- real time, all necessary inputs for the event table of all relay pairs matching the mode of operation and the location of the fault can be made.

The IEC standard inverse characteristic equation 3 of overcurrent relay (Juan et.al,2011) to use;

$$t_i = \frac{0.14 \times TMS}{\left[\frac{I_f}{I_{pickup}}\right]^{0.02} - 1} \tag{3}$$

Where: *TMS* is the time multiplier setting of the relay, I_f is the fault current seen by the relay, I_{pickup} is the pickup current of the relay. *TMS* and I_{pickup} should be determined in a special range as follows:

$$TMS_{min} \le TMS \le TMS_{max}$$

$$I_{pickup\ min} \le IP \le I_{pickup\ max}$$

To ensure the selectivity, the operating time of Backup Relays (t_b) should have enough delay time from Primary relays (t_p) as CTI:

$$t_b - t_p \ge CTI$$

3.2 APS based on Real Time Calculated Settings

Adaptive protection is "an online activity that modifies the preferred protective response to a change in system conditions or requirements in a timely manner by means of externally generated signals or control action" (Rockefeller, 1988). The required settings are updated in online manner as per variation in fault current levels seen by relays during changing network conditions (IEEE, 2014).

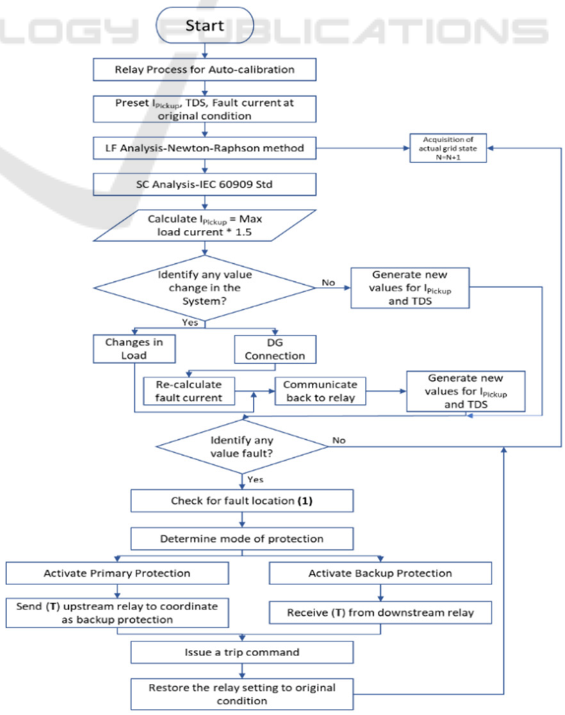


Figure 3: Flow chart of the proposed AOCR for MG.

The adaptive relay connected to the network will firstly do an auto-calibrate. After that, the parameters of I_{pickup}, Time Dial Setting (TDS) and the fault current will be preset to zero. Following, it will do a Newton–Raphson method of load flow analysis & Short Circuit Analysis by IEC 60909 Std. Then, it will calculate the I_{pickup} with required (1.5 times for example) safety margin (Sung et.al, 2013). However, if there is a change in configuration i.e. DG connections, the same is communicated through the relay which results in a new set of parameters for I_{pickup} and TDS.

The next step is identifying the fault and its location by using the overcurrent equation, which is denoted by "(**1**)" in the algorithm. The principle of overcurrent protection is shown;

$$I^j > I_{pickup} \quad (4)$$

In the overcurrent principle, the "Normal Condition", where there is no fault, relay will not trip circuit breakers (CB). "(**T**)" is the representation of the second condition, which is the short-circuit or fault condition. When I^j is greater the I_{pickup}, after determining the mode of protection, it issues a command for the right CB to trip. Once the fault is cleared, it will restore to the original condition. It continues to do the same process for the next iteration where N = N + 1.

3.3 APS Algorithm in the Distribution Network

The above flow chart can be coded in Fuzzy logic controller for real time use. With SCADA, the Fuzzy Logic Designer application for Microgrid Central Controller (MGCC) makes the IED's completely adaptive. The application needs the power network's model for load flow calculation as well as measurement integration for collecting online data by using communication protocols. Real-time simulation uses the execution of new solutions in monitoring, the control system, and automation.

3.4 AOCR Block Diagram

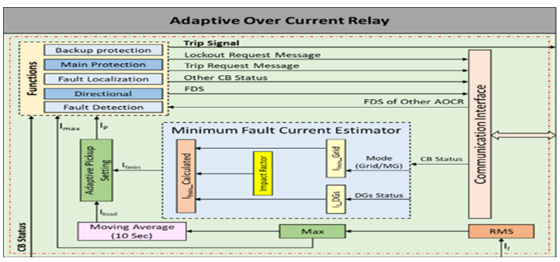


Figure 4: AOCR block diagram.

4 SIMULATIONS SET UP

4.1 Site Data

In this study, the IEEE 44 bus radial feeder existing DN is adopted. ETAP software (Etap 21.0.1 version) is used to draw the detailed SLD, simulate the LFA, SC & CTI studies. Relays like SE P122/ P139, Tr - O/C & E/F, busbar/ feeder management protection, all existing Switchgears and devices were site verified. Numbering of buses and sources done, the master SLD finalized before create a site SLD for the simulations. All required permits, tools, methodology secured, on-site verifications assisted by an expert.

4.2 Description of ETAP Simulation Set Up

All required analysis was performed in a personal computer with an Etap dongle and in the 9-bus subnetwork (MG model). The new feature in the SCADA system is the state estimation concept which is used by the ETAP real-time application. It supports the advancement of the information and automation schemes for autonomous protections.

SGs features were identified with the help of Etap simulations as per Figure 4.2 with 2 DG's for 4 loads connected to "Chiller bus 7" which is designed as the emergency backup chillers to cater the critical loads.

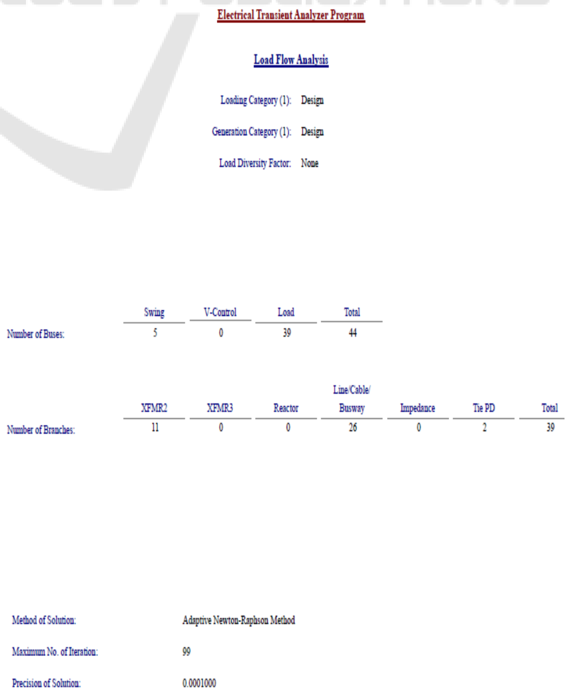


Figure 5: Summary DN data.

5 ETAP SIMULATION RESULTS VERIFIED OF SELECTED IEEE-9 BUS SUBSYSTEM

5.1 Load Flow Analysis Reports

5.1.1 LFA by Adaptive Newton Raphson Method

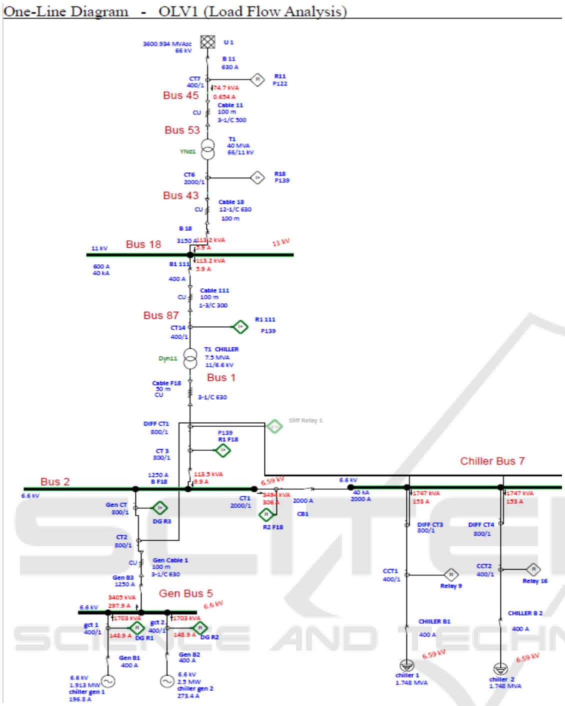


Figure 6: LFA.

5.1.2 LFA Report Summary of Generation, Load and Demand

Table 3: LFA.

Description	MW	MVar	MVA	%PF
Total Demand-Source (Swing)	2.97	1.80	3.48	85.6Lag
Total Motor Load	2.38	1.47	2.80	85.0Lag
Total static Load	0.59	0.37	0.70	85.0Lag
Apparent Loss	0.003	-0.041		
System Mismatch	0	0		
No. of iterations	01			

5.2 Short Circuit Analysis Reports

SCA by IEC 60909 Standard of selected network carried out, for simplicity we have taken the reading of 3 phase faults. With different SG's the values of Fault Current (KA) are found to be different and is tabulated in Table 4.

5.3 Protection Coordination Simulations

CTI Simulation with Fault Creation -Grid mode (Curve settings verifications by ETAP 21.0.1 software (Star Coordination option). The response sequence to the fault simulation for SG #1 was given below.

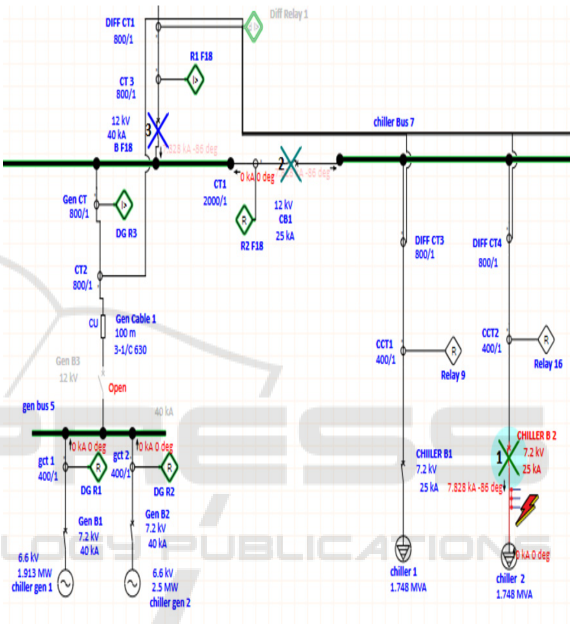
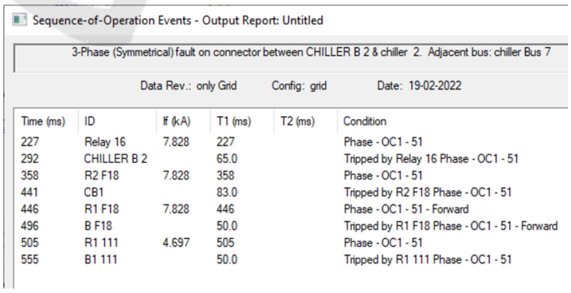


Figure 7: SG 1 Fault simulation- relays response Sequence.


Sequence-of-Operation Events - Output Report: Untitled

3-Phase (Symmetrical) fault on connector between CHILLER B 2 & chiller 2. Adjacent bus: chiller Bus 7

Data Rev.: only Grid Config.: grid Date: 19-02-2022

Time (ms)	ID	If (kA)	T1 (ms)	T2 (ms)	Condition
227	Relay 16	7.828	227		Phase - OC1 - 51
292	CHILLER B 2		65.0		Tripped by Relay 16 Phase - OC1 - 51
358	R2 F18	7.828	358		Phase - OC1 - 51
441	CB1		83.0		Tripped by R2 F18 Phase - OC1 - 51
446	R1 F18	7.828	446		Phase - OC1 - 51 - Forward
496	B F18		50.0		Tripped by R1 F18 Phase - OC1 - 51 - Forward
505	R1 111	4.697	505		Phase - OC1 - 51
555	B1 111		50.0		Tripped by R1 111 Phase - OC1 - 51

Figure 8: SG 1Fault simulation - relays response Report.

For each simulations the curve settings reviewed and corrected for sequence and t_{op}. A standard inverse IEC curve is used to carry out the automatic coordination of overcurrent protections (IEC & IEEE, 2009). Figure 9 below shows the CTI of relays operation with Fault Simulation with SG #3 (PG + 2DG's).

With different SG's the values at which the relays tripped are found to be different and the obtained information tabulated as Table 4. The highlighted values set in the same relay with the same fault but in different configuration of sources clearly demonstrates the needs for APS.

Table 4: CTI Report Summary.

SG #	SG Configuration	Relay Pair	Fault Current (KA)	$I_{pickup\ (A)}$	T1 in ms
1	PG Source only	R 16- R2F18 R1F18	7.83	184 790 784	0.1 0.12 0.15
2	PG+ 1DG	R 16- R2F18 R1F18	9.31	184 1100 784	0.1 0.12 0.15
3	PG+ 2DG	R 16- R2F18 R1F18	10.89	184 1540 784	0.1 0.12 0.15
	Island- 1DG (not used for AOCR settings)	R 16- R2F18 DGR3	1.48	184 320 312	0.1 0.12 0.14
4	Island - 2DG	R 16- R2F18 DGR3	3.06	184 620 620	0.1 0.12 0.14

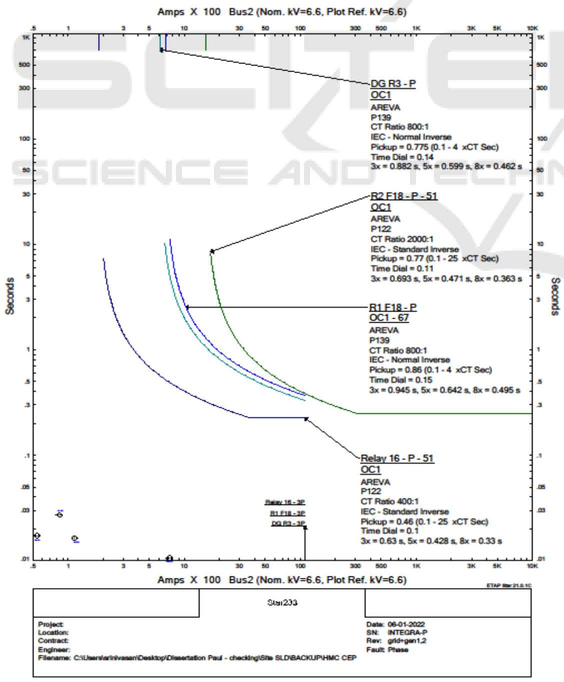


Figure 9: SG 3 CTI of relays response Sequence.

From different analysis done for combinations of power sources with its optimum curve settings of relay pairs the input values for relay programming established. The relay R2F18 selected being common to all SGs for the adaptive settings.

6 AOCR FUNCTIONAL VERIFICATION

We used SE P139 relay, 4 Automatic Settings Groups programmed with Pre-Calculated values of pick up and Time dial derived from Fault Simulations and CTI settings respectively. The Relay PLC programming (Easergy Studio V9.3.1-SE) also defined the relay pairs for CB's control actions. The existing DN panels were set up for HIL tests by secondary injection method. The relay test block wired properly, connected the Omicron CPC 100 test kit and relay control established through ethernet.

Figure 10: HIL Set up.

The results of L-L SC simulation results recorded as;

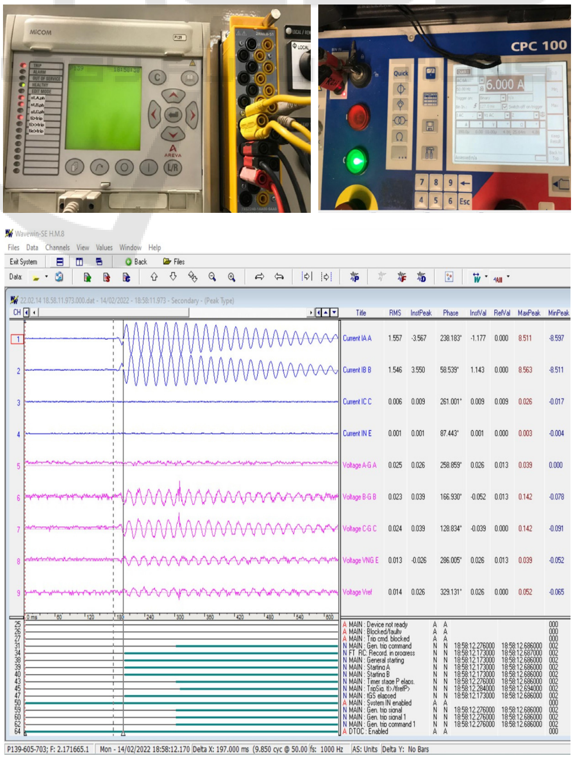


Figure 11: AOCR L-L Fault Simulation.

Detailed system generated reports like File Information, Analog Summary, Events/Sensors Activity Log and Summary downloaded.

Also, results of L-E Fault response graph recorded as;

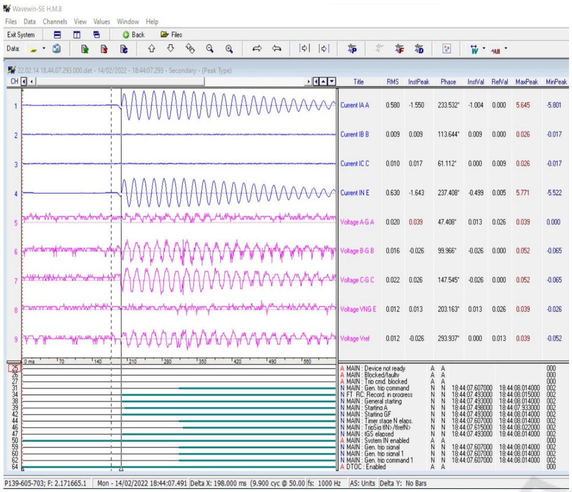


Figure 12: AOCR L-E Fault Simulation.

7 CONCLUSION AND FUTURE SCOPE

The adaptiveness of the relay functions verified against programmed values. An algorithm has been proposed for the AOCR to implement in Microgrids with SCADA and Etap real time. Since IEC-61850 supplies appropriate peer-to-peer connection between distributed IEDs, by using 'generic object-oriented substation events' (GOOSE) technology, we may achieve any data transmission through the network within 4ms, so this protocol is being used in all modern grids DNs [Tian et.al, 2016]. AOCR with technologies such as AI and IoT, which uses real-time values expected to have widespread use in future MG.

ACKNOWLEDGMENT

My sincere thanks to Er. Dhafi Rashid Al Marri, ED-Engineering, HMC, Doha, Qatar for his guidance.

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APPENDIX

Tools and Components Referred during Study

1. MG Controllers
   SEL- PowerMAX with RTAC, SEL 3555, 3560 and 651R
   SE - Ecostructure Power, Micom P40 easergy series
   Opus 1 solutions – GridOS-DER EMS
   GE – U90+ Multilin
2. Overcurrent protection devices for MG Controllers
   SE -P139/ GE -P14D/ Micom P446
   Siemens - Siprotech/ Reyrolle 7SR/ ABB – REF 615
3. MG Simulation tools
   EMTP & ETAP Realtime
   MATLAB/Simulink -Java Agent Development Environment
   DigSilent/ Opal RT/ Siemens PSS/ DER –CAM
   EPRI –OpenDSS/ GridLAB -D
4. Plug and Play type DER's
   Eaton - Heila Edge (Solar)
   Cat BDP 250 (ESS invertor)
   Alpha structure (Carlyle and SE)/ Bloom Energy
   Siemens
5. Communication and compliance needs
   IEEE 2030.7 & 8, IEC 61850 -9.2LE, Modbus, RS232/485, IEEE 1547/242/C 37, IEC 61439 (LV)/ 62271 (HV) for SWGR & Controls
6. Other Desirable Controller features
   PLC compatibility, Load sharing/Shedding, Voltage/frequency regulation, Power and PF control, SER/Oscillography recorder, Short and open circuit protection, Trip and close controls, Self-diagnosis/self-calibrations