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Developing an Adaptive Protection Scheme Towards Promoting the Deployment of Distributed Renewable Sources in Modern Distribution Networks: Operational Simulation Phase

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***Abstract*— The large-scale integration of renewables into the electricity grid as distributed generation sources for providing clean energy supply together with the recent introduction of the smart grid concept, have accelerated the need to modernize the existing protection schemes to accommodate the challenges originated from distributed generation. This paper presents an adaptive protection scheme that has been developed to allow automatic adjustment of optimal relay settings in response to multiple network topologies and unexpected variations arising from renewable energy systems integration towards promoting their deployment in modern distribution networks. A Simulink model is developed to simulate the operation of the adaptive protection scheme, being interlinked to a linear-programming technique to allow optimizing the relay settings in response to dynamic changes of network topology associated with the integration of distributed generation sources. The performance of the developed adaptive protection scheme in accommodating the dynamic changes of network topology has been assessed under two proposed network topologies using a small-scale network that has been built in the lab as part of experimental work for the purpose of implementing the adaptive control unit. Results have demonstrated the effectiveness of the developed approach in optimizing the relay settings in response to the subjected topology changes, achieving minimum relay trip times while ensuring a suitable relay coordination is satisfied in each of the tested network topologies.**

Keywords — Adaptive Protection Scheme, Distributed Generation, Optimal Relay Settings, Relay Coordination, Simulation Platform

I. INTRODUCTION

The ongoing Net-Zero energy transition plays a key role in promoting the large-scale deployment of renewables as Distributed Generation (DG) sources for providing clean energy supply to electrical power networks while addressing energy security and global warming concerns [1], [2]. DG sources can support the decarbonization of the energy sector by replacing fossil-fuels with clean small-scale decentralized distributed energy resources such as PV panels, wind turbines, fuel cells, or micro-turbines, usually integrated near to load demand centers to allow reducing distribution losses, while providing other potential benefits including voltage profile improvement, security enhancement of critical loads, provision of ancillary services and reduction of expensive and carbon-intensive spinning reserve requirements together with low-carbon environmental impact [3]. With the current energy crisis Worldwide, distributed renewable resources became key enablers to address the increased energy security concerns while realizing the ambitious climate goals. However, their integration into electrical power networks brings major technical challenges in terms of protection, control and reliability of modern distribution networks. Conventional protection schemes were originally designated for radial distribution networks with unidirectional power flow, which were commonly protected using overcurrent relays (OCRs) based on fixed fault current levels. The interconnection of DG units will consequently transform the radial topology into meshed structure with bidirectional power flow, affecting both the magnitude and direction of fault currents in various parts of the system [4]. Moreover, future smart grids will be subject to significant changes and unexpected grid states that may alter the network topology such as the addition or disconnection of a new incoming generation unit, the addition of a new line, the sudden line outage occurrence and the operation of DG units in either grid-connected or islanded mode. Such variations will cause the power networks to suffer from the mal-operation of protective devices as result of consequent changes in fault current levels and network impedances, thus degrading the selectivity of protection systems [5]. To help unlocking the full potential of distributed renewable generation while overcoming the impact of its large-scale integration on the protection of electrical power networks, a new paradigm, architecture and philosophy known as **"Adaptive Protection Scheme"**, is proposed to respond to several variations in network topology arising from DG integration. Adaptive protection can be defined as an "online procedure that automatically adjusts the relay settings whenever the grid operating conditions alter, in order to guarantee a selective operation in all possible network topologies" [6]. The implementation of adaptive protection scheme can be achieved via two phases. In phase-1, the relay setting groups are calculated using an optimization algorithm for all possible network topologies, then stored into digital relays in an offline manner. In phase-2, a central controller monitors the grid operating state and uses the offline settings to configure the relays properly, based on the prevailing network topology. Therefore, phase-2 is an online procedure, in which the protective system is able to monitor and update the relay settings in accordance with distribution network status, based on the offline analysis [6]. Several research studies [7]–[11] have been conducted in the literature for solving the relay coordination problem using robust mathematical optimization algorithms. However, few studies [12], [13] were found investigating the operation and control of the adaptive protection scheme for providing optimal relay settings in response to network topology changes, which represents key components in assessing the performance of the adaptive protection approach and the opportunities of its application within modern distribution networks. The work through this research has been conducted on two phases. The first one, which is presented in this paper, aims to develop a simulation platform linking the operation of the adaptive protection scheme with the optimization process of relay settings for different network topologies, thus providing an online adjustment of optimal relay settings in response to dynamic changes of network topologies, allowing to integrate more distributed renewable resources in modern distribution networks towards meeting the Net-Zero goal. The second phase aims to investigate the hardware implementation of the associated adaptive control unit for enabling real-world application of the adaptive protection schemes within modern distribution networks. To allow for experimental validation, a small-scale three-bus system with meshed-structure has been built in the lab and used as case study for this purpose. A MATLAB Simulink model is developed to simulate the test case system under two proposed network topologies, where the resulting load flow and fault current signals were linked to a linear programming algorithm so that the relay settings are automatically optimized and adjusted in an online manner in response to network topology changes. Simulation results have showed that the developed adaptive protection scheme has allowed operating the relays in minimum tripping times while satisfying suitable coordination time intervals under each of the tested network topologies.

II. Relay Coordination Problem Formulation

A typical inverse-time OCR consists of two settings: the first one is the pickup current (I_p) which defines the minimum value of current for which the relay begins to operate, while the second is the Time Dial Setting (TDS) which adjusts the OCR inverse characteristics and hence controls the time delay before a relay begins to operate whenever the fault current reaches a value greater than or equal the pickup current. The main aim of the relay coordination problem is to determine the optimum values of TDS and I_p settings that can minimize the total operating time of all protective devices. Therefore, the objective function of the relay coordination problem is formulated for minimizing the sum of all relay operating times as given by (1) and (2) [14], to ensure faster relay response for both primary and backup relays, where the relay settings represent the decision variables assigned to minimize the given objective function.

$$min \sum_{k=1}^{n} (t_{op,k}) \tag{1}$$

$$t_{op,k} = \text{TDS} \frac{\text{A}}{(I_F/I_p)^{\ B} - 1} \tag{2}$$

Where, n is the number of relays installed in the system, $t_{op,k}$ is the operating time of relay ‘k’, TDS is the relay time dial setting, I_p is the pickup current setting, I_F is the fault current passing through the relay, A and B are constant parameters representing the relay characteristic curve type.

The objective function given in (1) is subject to the following set of constraints: firstly, the selectivity constraint given by (3), which states that in the event of fault, the primary relay should first trigger to clear the fault. If the primary relay fails to operate, the backup relay should then clear the fault after a predefined delay time referred as the coordination time interval, typically ranging from 0.2 to 0.5s. Secondly, the limitation constraints which specify the boundaries of relay settings; this includes TDS and Ip settings as given by (4) and (5), respectively.

$$CTI_{min} \leq T_{backup} - T_{main} \leq CTI_{max} \tag{3}$$

$$TDS_{min} \leq TDS \leq TDS_{max} \tag{4}$$

$$I_{p\_min} \leq I_p \leq I_{p\_max} \tag{5}$$

where, T_{main} and T_{backup} are the main and backup operating time, respectively, CTI_{min} and CTI_{max} are the minimum and maximum coordination time intervals between the primary and its backup relay, respectively, TDS_{min} and TDS_{max}, are the minimum and maximum limits of TDS, respectively, typically ranging from 0.1 to 1.1s [14], I_{p_min} and I_{p_max} are the minimum and maximum boundaries of I_p settings, respectively. It should be noted that the value of I_p should be selected between the full load current and the minimum fault current passing through the corresponding relay.

III. Case Study

To enable investigating the hardware implementation of the adaptive protection control unit, a small-scale three-bus system has been built in the lab and used as case study to simulate and in the next-phase experimentally validate the real-time response of the proposed adaptive protection scheme in solving the relay coordination problem and optimizing the relay settings in response to sudden variations occurring in grid networks. The built network consisted of two generation units interconnected with meshed structure as shown in Fig. 1. The primary generation unit represents uninterruptable power supply that is used to simulate the main utility grid, while the second is considered an additional DG incoming source to be integrated in grid-connected mode. The system is protected via four OCRs, namely K_1, K_2, K_3 and K_4, each is installed on a line feeder as shown in Fig. 1. All data used in simulating the generation units, line feeders and load demands were based on lab-scale ratings, as given in Table I and Table II. It should be noted that the lab equipment used in building up this network (power supply units, transmission line models and load impedances) are intended for simulating a high voltage level (within hundreds of kilovolts) using a scaling factor of 1:1000. Two proposed network topologies were examined to assess the performance of the adaptive protection scheme for providing optimal relay settings in response to sudden changes of network topologies. The first one simulates the network when only supplied from the utility grid prior to DG integration, while the second investigates the impact of integrating a DG incoming source in grid-connected mode on the response of the proposed adaptive approach for accommodating the dynamic changes of network topology being altered from radial into meshed structure. A detailed explanation of the developed simulation platform for modelling the operation of the adaptive protection scheme, is outlined in the next sections.

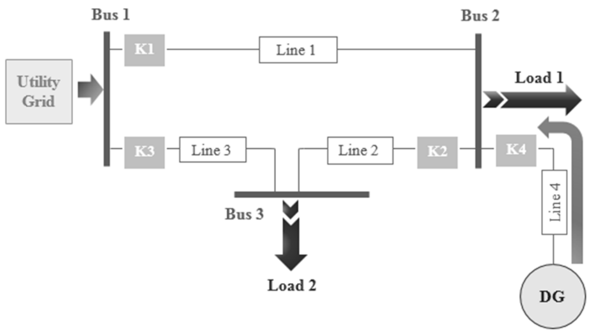

Fig. 1 Single line diagram of the small-scale three-bus system

TABLE I. LINE DATA OF THE THREE-BUS SYSTEM

Line	Type	R (Ω)	L(mH)	C (uF)
1	PI-Line Model	3.3	80	0.2
2	PI-Line Model	13	290	1.0
3	PI-Line Model	13	290	1.0
4	PI-Line Model	13	290	1.0

TABLE II. GENERATION AND LOAD DATA OF THE THREE-BUS SYSTEM

Generation unit	Voltage (V)	Load	Power (W)
Utility Grid	160	Load 1	195
DG incoming unit	160	Load 2	195

IV. DEVELOPING A MATLAB SIMULATION PLATFORM

A MATLAB-Simulink model is developed to simulate the operation of the adaptive protection scheme in response to dynamic changes of network topology, by firstly conducting a load flow and short circuit analysis in a Simulink environment, being then interlinked to a linear-programming algorithm that is integrated to enable solving the relay coordination problem in each of the tested network topologies using the outgoing current signals from the simulated load flow and short-circuit analysis. The main goal of the combined architecture is to present an adaptive protection system featuring an integrated optimization process of relay settings in response to network topology changes resulting from the integration of renewable DG sources.

A. *The Developed Simulink Model*

The developed Simulink model tailored to investigate the operation of the adaptive protection scheme consisted of four OCR-based control setups; each is composed of a circuit breaker controlled by an OCR sub-model. The relay coordination problem is solved using the interior-point method via a linear programming subroutine that is integrated via an optimization function block to allow computing the optimum relay settings that can minimize the total operating time of all OCRs installed within the built network while satisfying the selectivity and limitations constraints described earlier in Section II. The MATLAB Simulink toolbox is used to conduct a load flow under normal operating conditions to measure the full load currents of the line feeders in each of the tested network topologies, which were used to select suitable Ip values within the minimum and maximum limits of I_p as specified by the limitation constraints in Section II. Following the load flow simulation, the system is subjected to unsymmetrical single line-to-ground fault for measuring the fault currents passing through K_1, K_2, K_3 and K_4 at a given fault location. The measured values of fault currents were then used as data input to the optimization function block with the latter receiving online signals from the conducted short-circuit analysis to optimize the TDS settings of the developed OCR sub-models. The optimized relay settings are then sent back to the OCR sub-models for energizing the trip signals via the circuit breakers in an online manner to perform the required action. All breakers are operating in external mode and controlled via an external signal received from the OCR sub-models that will be described in next section. Fig.2 illustrates the developed Simulink model for the adaptive protection scheme.

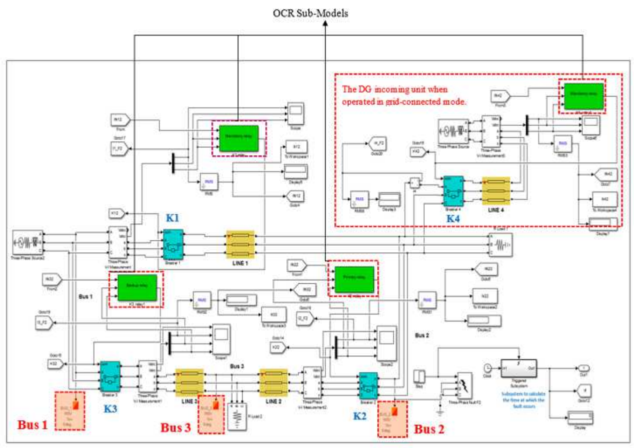

Fig. 2 The Developed Simulink Model of Adaptive Protection Scheme

B. *The Developed Overcurrent Relay (OCR)-Sub-Models*

A MATLAB Simulink sub-model is developed to construct an OCR block. This involved arithmetic operators which compare the full load current measurements of line feeders with the selected I_p settings to detect the event of any fault occurrence. The outgoing signals from these operators are then fed to a logical AND gate to enable controlling the operation of the circuit breaker in case of symmetrical and unsymmetrical faults. A time delay is provided to the relay sub-model to observe the breakers operating time during the conducted fault, which is calculated using the optimized TDS settings received from the optimization function block described later in Section C, based on standard inverse-time curve characteristic of OCR as given earlier by (2). Fig. 3 shows the designed setup used to construct each of the four OCR sub-models installed within the considered network.

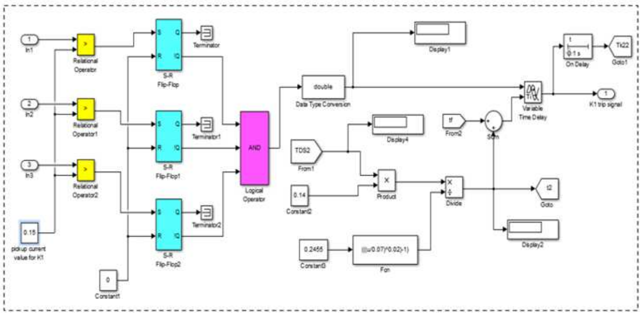

Fig. 3 The Designed Set-up used to construct each of the OCR Sub-Models

C. *The Integrated Relay Settings Optimization Process*

The process of optimizing the relay settings is implemented using an optimization function block that receives incoming signals from the measured fault currents when the system is subjected to a fault at a given location. This block generates a MATLAB execution code for solving the relay coordination problem via the interior-point method, a linear-programming subroutine that is integrated to compute the optimal TDS values which can minimize the operating time of all OCRs while satisfying the problem set of constraints as given earlier in Section II. The outgoing signals from the optimization function block are continuously sent to the developed OCR sub-models during the system simulation to manipulate an online optimization process. Fig. 4 shows a block diagram for the integrated relay settings optimization process.

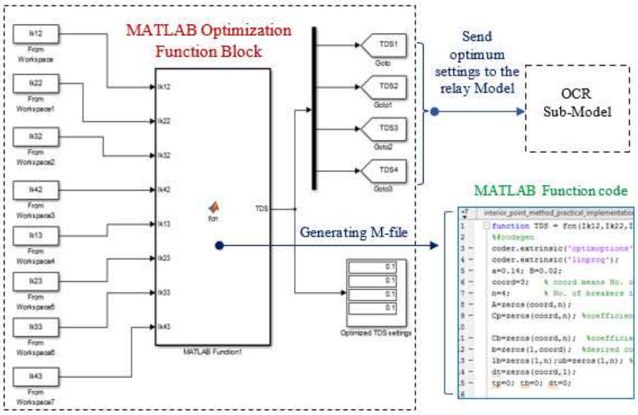

Fig. 4 The integrated Optimization Function Block Diagram

V. Results of Optimized Relay Settings

As mentioned earlier, the developed simulation platform is tested under two proposed network topologies to investigate the impact of integrating a DG incoming source on the performance of the proposed adaptive protection scheme in responding to corresponding variations in network topology. For each network topology, the primary and backup (P/B) relay pairs are identified for a fault conducted at bus 3 (F_3).

A. *Network Topology (1): Prior DG integration*

The first topology represents the system when only fed from the utility grid prior to DG integration. In this case, the incoming DG unit and the attached line feeder will be omitted from the considered network with the latter being protected via only three OCRs: K_1, K_2 and K_3, while K_4 became deactivated in the absence of the DG incoming source. In case of fault at bus 3 (F_3), K_2 and K_3 should trip first to clear the fault as primary relays, while K_1 acts a backup relay for K_2. Table III shows the results of optimized TDS settings for K_1, K_2 and K_3 under network topology (1), computed using the integrated optimization function block based on the conducted load flow and short circuit analysis obtained from the MATLAB simulation window. As can be seen from Table III, the results of optimized TDS are all lying within the range of feasible solutions as given per the limitations constraint in Section II. Accordingly, Table IV shows the results of minimized trip times for the identified P/B relays at fault F_3 under network topology (1), adjusted by the integrated optimization function block using the optimized TDS settings, together with the associated coordination time intervals between the identified P/B relay pairs satisfying no more than 0.5s of predefined selectivity constraint.

TABLE III. Results of Optimized TDS Under Topology 1

Relay	**K_1**	**K_2**	**K_3**
TDS	0.1	0.1209	0.1

TABLE IV. Results of Minimized Relay Trip Times and Coordination Time Interval at Fault F_3 under Topology 1

Description	**Item**	**Trip time**
Primary 1	K_3	0.48s
Primary 2	K_2	0.51s
Backup	K_1	0.91s
Coordination interval	CTI_{k2-k1}	0.40 s

B. *Network Topology (2): With integrated DG-unit*

The second topology investigates the impact of integrating a new incoming DG unit on the performance of the simulated adaptive protection scheme for adjusting optimal relay settings in response to dynamic changes in load flow and fault current levels. A secondary generation unit, operating in grid-connected mode, is integrated at bus 2 through an additional feeder to supply the load demands in parallel with the utility grid. As can be seen from Fig. 1, an additional breaker is installed to protect the supplementary feeder, therefore the considered network became protected via four OCRs: K_1, K_2, K_3 and K_4, when tested under network topology (2). A new set of P/B relay pairs is identified under this topology at fault F_3, where K_2 and K_3 act as primary relays to clear the fault, while K_1 and K_4 act as backup relays for K_2 in case it fails to operate. Under this topology, the system is re-simulated using MATLAB Simulink toolbox to run a new load flow and short circuit analysis and thus re-optimize the relay settings in response to corresponding variations in network topology. Table V shows the results of the new optimized TDS settings for K_1, K_2, K_3 and K_4 under network topology (2), computed using the integrated optimization function block based on the newly conducted load flow and short circuit analysis obtained from the MATLAB simulation window. As can be seen from Table V, the results of optimized TDS are all lying within the range of feasible solutions as given per the limitations constraint in Section II Accordingly, Table VI shows the results of minimized trip times for the identified P/B relays at fault F_3 under network topology (1), readjusted by the integrated optimization function block using the newly optimized TDS settings, together with the associated coordination time intervals between the identified P/B relay pairs satisfying no more than 0.5s of predefined selectivity constraint.

TABLE V. RESULTS OF OPTIMIZED TDS UNDER TOPOLOGY 2

Relay	**K_1**	**K_2**	**K_3**	**K_4**
TDS	0.1	0.2471	0.17	0.1

TABLE VI. RESULTS OF MINIMIZED RELAY TRIP TIMES AND COORDINATION TIME INTERVALS AT FAULT F_3 UNDER TOPOLOGY 2

Description	**Item**	**Trip time**
Primary 1	K_3	0.88s
Primary 2	K_2	0.99s
Backup 1	K_1	1.25s
Backup 2	K_4	1.496s
Coordination interval 1	$CTI_{k2\text{-}k1}$	0.2536s
Coordination interval 2	$CTI_{k2\text{-}k4}$	0.50s

VI. SIMULATION RESULTS AND DISCUSSION

To observe the response of the simulated adaptive protection scheme in executing the optimized relay settings according to subjected topology changes as explained in Section V, the considered network is simulated during fault F_3 under each of the tested network topologies and simulation results are captured for both primary and backup relay operations. Fig.5 shows the primary response of K_1, K_2 and K_3 during fault F_3 under network topology (1), indicating that K_3 has tripped first at 0.584s while K_2 has completely isolated the fault at 0.614s. As can be seen from Fig. 5, the backup relay K_1 is kept in operation and this is indicated by displaying a HIGH output trip signal, given that K_2 and K_3 have completely cleared the fault as primary relays at the aforementioned instants. From Fig. 5, the trip time signals of primary relays K_3 and K_2 are seen initiated from the time the fault has been issued at 0.1s up till 0.584s and 0.614s for K_3 and K_2 respectively, resulting in relay trip times of 0.484s and 0.514s for K_3 and K_2 respectively, thus achieving nearly the same minimized results computed in Table IV for primary operation. Regarding the backup operation at fault F_3, this is simulated by keeping the primary relay K_2 operating during the fault F_3 and observing the response of its backup relay peer K_1. Fig. 6 shows the backup response of K_1 during fault F_3 under network topology (1), when the primary relay K_2 fails to operate. As can be seen from Fig. 6, the current passing through K_2 is maintained in operation until the fault is fully interrupted by the backup relay K_1 at approx. 1s. From Fig. 6, the trip time signal of the backup relay K_1 is seen initiated from the time the fault has been issued at 0.1s up till approx. 1s when the fault has been totally cleared, resulting in a relay trip time of about 0.9s as computed in Table IV for backup operation. To allow observing the executed coordination time interval between the identified P/B relay pair (K_2/K_1) under network topology (1), a virtual trip time signal is illustrated in Fig. 6 for primary relay K_2 when the latter supposed to operate at 0.614s to trip the fault while K_1 is seen actually clearing the fault at approx. 1s, thus achieving 0.4s of coordination time interval between K_1 and K_2, as obtained in Table IV.

Fig. 7 shows the primary response of K_1, K_2, K_3 and K_4 during fault F_3 under network topology (2), indicating that K_3 has tripped first at 0.9837s while K_2 has fully interrupted the fault at 1.105s. As can be seen from Fig. 7, the backup relays K_1 and K_4 are kept in operation, given that K_3 and K_2 have completely cleared the fault as primary relays at the aforementioned instants. From Fig. 7, the trip time signals of primary relays K_3 and K_2 are seen initiated from the time the fault has been issued at 0.1s up till 0.9837s and 1.105s, for K_3 and K_2 respectively, resulting in relay trip times of 0.8837s and 1.005s for K_3 and K_2 respectively, thus achieving nearly the same minimized results computed in Table VI for primary operation. Fig. 8 shows the backup response of K_1 and K_4 during fault F_3 under network topology (2), when the primary relay K_2 fails to operate. As can be seen from Fig. 8, the current passing through K_2 is maintained in operation until getting reduced at 1.35s when the backup relay K_1 tripped first to be then fully interrupted by K_4 at 1.596s. From Fig. 8, the trip time signals of the backup relays K_1 and K_4 are seen initiated from the time the fault has been issued at 0.1s up till 1.35s and 1.596s for K_1 and K_4 respectively, resulting in relay trip times of 1.25s and 1.496s for K_1 and K_4 respectively, as computed in Table VI for backup operation. To allow observing the executed coordination time intervals between the identified P/B relay pairs (K_2/K_1, K_2/K_4) under network topology (2), a virtual trip time signal is illustrated in Fig. 8 for primary relay K_2 when the latter supposed to operate at 1.105s while K_1 and K_4 are seen actually tripping at 1.35s and 1.596s, respectively, to clear the fault thus achieving coordination time intervals of 0.25 s between K_2 and K_1, and 0.49s between K_2 and K_4, approximately equivalent to those obtained in Table VI.

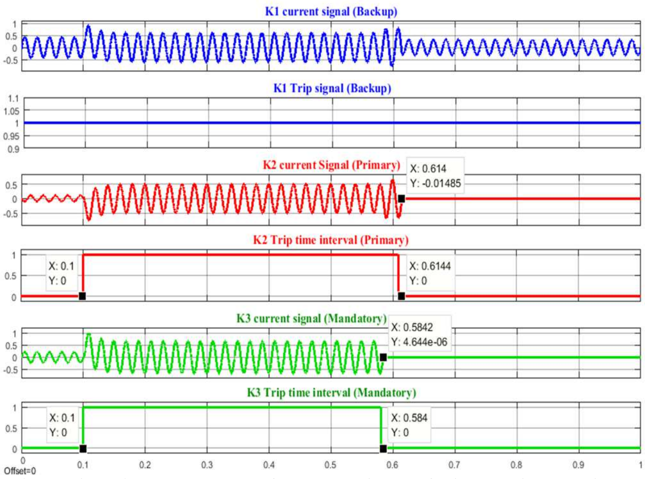

Fig. 5 The primary response of K_1, K_2 and K_3 at fault F_3 under Topology1

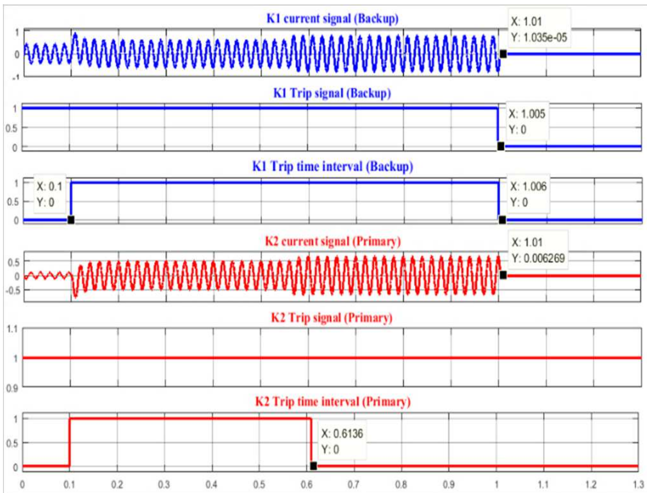

Fig. 6 The backup response of K_1 and K_2 at fault F_3 under Topology 1

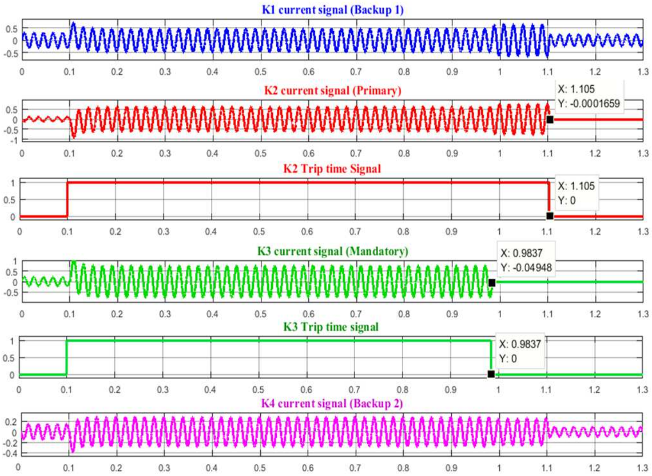

Fig. 7 The primary response of K_1, K_2, K_3 and K_4 at fault F_3 under Topology 2

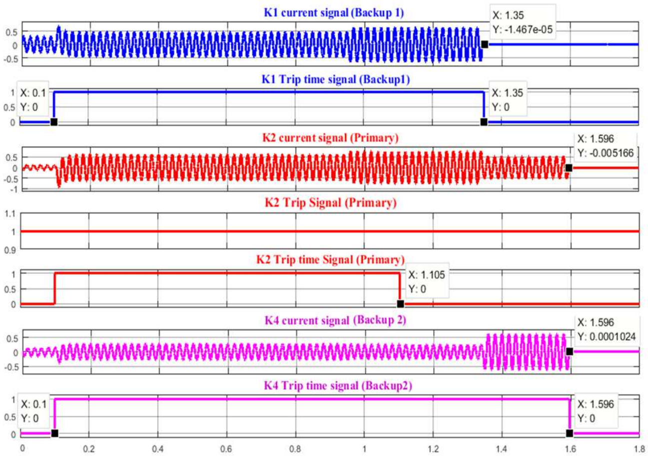

Fig. 8 The backup response of K_1, K_2, and K_4 at fault F_3 under Topology 2

CONCLUSION

This paper develops an adaptive protection scheme allowing to automatically adjust optimal relay settings in response to dynamic changes of network topologies arising from the deployment of distributed renewable resources in electrical power networks towards achieving the Net-Zero goal. A MATLAB Simulink model is developed to simulate the operation of the adaptive protection scheme, featuring an integrated optimization algorithm to adjust the optimal relay settings in response to network topology changes associated with DG integration. Two proposed network topologies were investigated to assess the performance of the adaptive protection scheme in accommodating the variations of fault current levels prior and after the integration of a DG incoming source operating in grid-connected mode. Simulation results have showed the relays are operating in minimized relay trip times while ensuring a suitable relay coordination is satisfied in each of the tested network topologies, thus reflecting the effectiveness of the developed adaptive protection model in responding to different network topologies while avoiding miscoordination of relay settings. Future work should address the opportunities of implementing the adaptive protection control unit to enable observing the real-time response of adaptive protection schemes towards enabling their application in modern distribution networks.

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