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RESEARCH PAPER

Protection Challenges of Green Technology in Power Distribution System

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Abstract

The mitigation of future electricity demand is highly dependent upon the integration of green energy technology. Most countries realise the importance of green energy and are given support policies for the encouragement of power integration from green energy sources (GES). The effect of bulk power integration from GES causes stability issues in the power system. The solar and wind energy technologies have been discussed in this paper. Issues relating to integration of GES in the distribution system have also been highlighted. It also describes the desired protection of the distribution network with GES. The coordination issue of auto recloser has been explained in depth. The paper narrates the challenges to green energy technology implementation in the distribution system. Finally, a solution for protection coordination is formulated and solved using a genetic algorithm between auto recloser and fuse using test system. Also, coordination with grid-side relay and fuse is validated. The results give optimised values of plug setting multiplier (PSM), time dial settings (TDS), and constants such as A, B, and x. The optimised values give the correct operating times of auto recloser (t_1) and fuse (t_2) and a coordinated time interval (CTI).

Keywords: auto recloser, green energy, over-current, optimisation, protection

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1. Introduction

The world realised the need for green energy technology and has reacted by increasing its use over the last 3 decades. Alternative energies are produced in various unique ways, like geothermal, bio-gas, liquid biofuel, solid fuel, bagasse, renewable municipal waste, bioenergy, marine, pumped storage, renewable hydropower, offshore and onshore wind, concentrated solar power, solar photovoltaic (PV), and solar. However, the share of wind and solar power is the more significant than hydropower. Figure 1 shows the data of IRENA (International Renewable Energy Agency) from 2015 to 2021, considering all the renewable sources and their installed capacity in MW. As shown in figure 1, solar and wind are the most dominant sources when compared to all others due to their independence in terms of

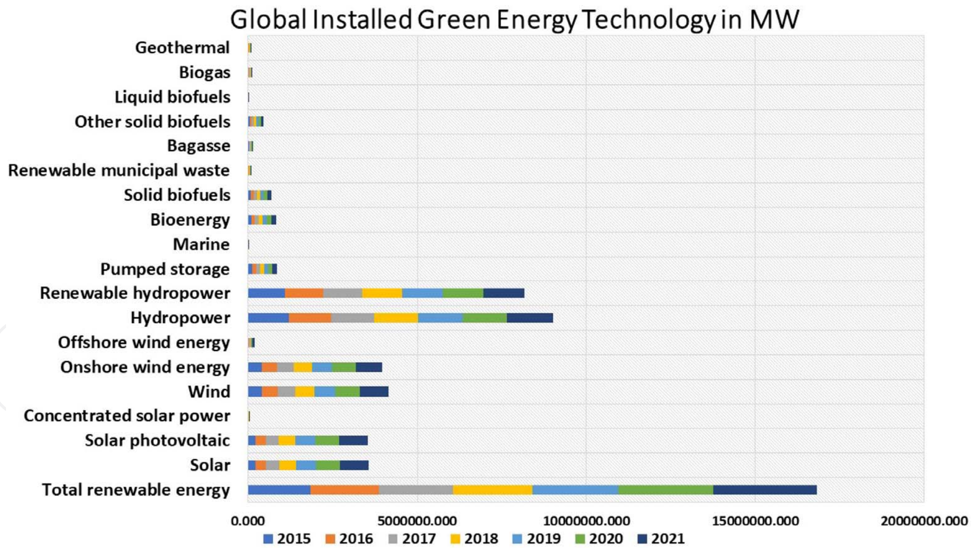

Figure 1. IRENA data of Global Green energy Source generation capacity from the year 2015 to 2021.

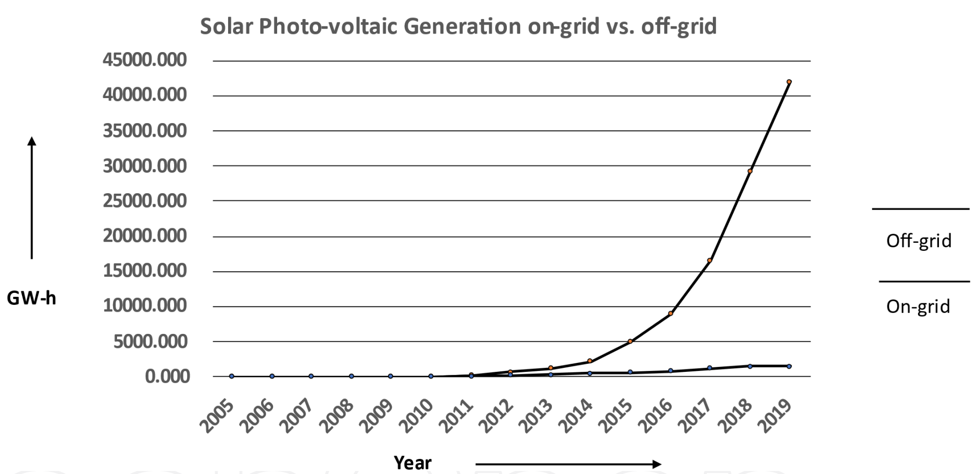

Figure 2. On-grid and off-grid solar photovoltaic generation in India from 2005 to 2019.

physical installation location. Figure 2 shows that solar on-grid installation is rapidly increasing, with a similar pattern for on-grid wind power as compared to off-grid. Wind and solar growth rates are approximately around 17% and 28%, respectively as calculated in 2015 [1]. The integration of solar and wind power generation creates many possibilities and, at the same time, many challenges to the power grid.

Research [2] has shown the impact of wind power generation on stability, which suggests an improvement in the protection scheme. The wavelet and deep learning-based schemes are proposed to improve the protection of the HV (High

Voltage) transmission line [3]. The power injected from renewable power sources is time-varying and partially controllable, resulting in the grid protection malfunctioning. The variable power control required operational flexibility [4]. The distance relay of power transmission lines is at high risk under the impact of renewable power penetration [5, 6]. The power distribution systems are mostly used over the current protection scheme, recloser, and fuses [7]. To date, almost all philosophies of the distribution system are based on the consideration of the redial flow of power from the source to the load, which is not the case with solar and wind sources [8]. The fault current contribution of hydropower is six times the rated current, whereas that of solar is two times, which is reduced significantly [9]. On the other hand, only renewable energy sources can compensate for the global energy crisis [10]. Secure protection of the distribution power system is challenging and needs to be properly addressed [11]. Coordinated protection based on synchrophasor has been proposed in the research work of [12]. Blackouts due to protection issues are highlighted and a guide for research has been shown in paper [13].

In this paper, section 2 shows the green energy technology and its configuration. Further, the control of green energy generation with the power network has been listed and explained in section 2. The coordination issue of fuse, overcurrent relay, and auto recloser has been presented in sections 3 and 4, with system data. The improved strategy to resolve the problem has been presented in section 5. The paper closes with the conclusion.

2. *Green energy technologies*

As narrated in section 1, solar power generation and wind power generation are the two fastest growing and most integrated energy sources. This section shows the development of these two green technologies and their work. Both of these green energy sources are weather dependent on a primary, secondary, and complex level. Further, both have power electronics converter technology usage in a wide context.

2.1. Wind generation system

The wind generation system with its various types of generation technology and control has been shown in figure 3. DFIG (doubly fed induction generator) has been used for the last two decades as a generator that is rotated by the wind turbine with a gear mechanism. This, with gear control using a partial capacity converter, results in low converter losses. Furthermore, the stator windings are directly connected to the grid in the DFIG type of wind generator, and converters are connected via the rotor of the DFIG to the grid. Hence, the slip-ring usage makes it difficult to grid fault in DFIG. To provide more flexibility and controllability, PMSG (permanent magnet synchronous generator) or synchronous generators are adopted. PMSG uses the full capacity of the converter and mostly gearless control. The gearless control

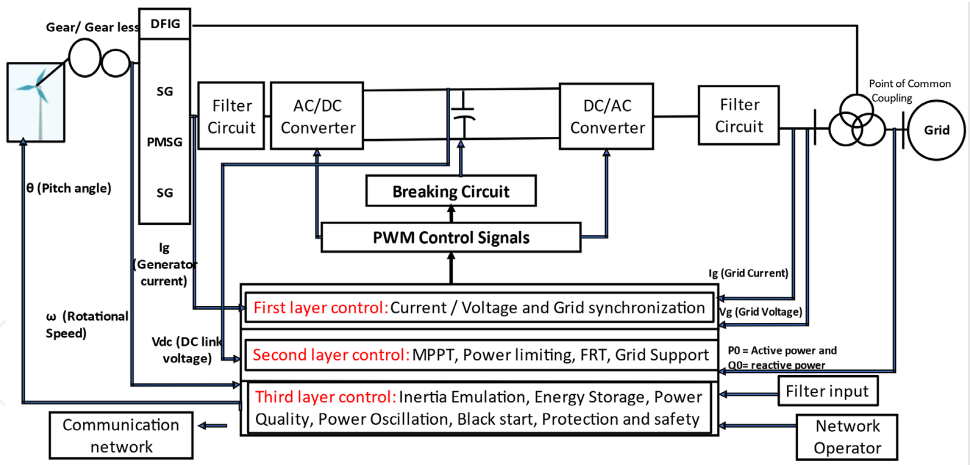

Figure 3. The control structure of wind generation system considering all the control loops.

makes it controllable for full power and speed ranges. PMSG technology-based wind generation has a few limitations, such as stress on the converter, the capacity of the converter, and losses in the converter. However, the share of PMSG keeps increasing in the wind generation technology. The control of wind generation technology can be classified as first layer, second layer, and third layer control. The most necessary control comes under the first layer, which is current/voltage control and grid synchronization, as shown in figure 3.

When the network operator sends the demand or fall, the mechanical and electrical control come into the picture. Secondary control is a must when the wind turbine generator is connected to the grid. The secondary control involves MPPT (maximum power point tracking), power limiting, FRT (fault ride through), and grid support. The MPPT algorithm senses the power output and then changes the rotational speed through pitch control. The fluctuation of wind results in a power change, which needs MPPT control. When heavy power is injected into the distribution grid as a result of MPPT, the voltage rises. So, to limit the heavy power flow, power limiting control has been used. Grid faults or faults near the generator must be controlled by controlling DC link voltage, grid side converter, breaking chopper, and pitch angle control using FRT. Primary control must respond as fast as possible to secondary control. Energy storage, black start, power oscillation damping, and power quality come in the third layer of control, which increases the efficiency of the overall wind generation system.

2.2. Solar power generation system

The driving forces such as power electronics technology advancement, PV cell technology success, and the price decrease of PV modules enable the rise in the

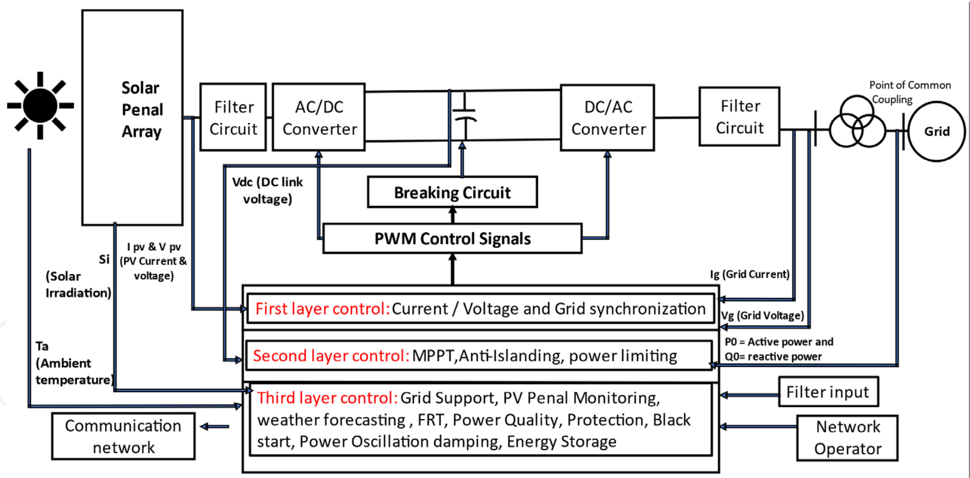

Figure 4. The control structure of solar generation system considering all the control loops.

integration of solar power into the grid. The PV system will be the main competitor in the future for the previous reasons discussed. Solar power generation, unlike wind power generation, does not require any mechanical system. The system without mechanical control makes it easy to install and operate. Solar power is generated by the PV effect, which enables solar energy to be converted into electricity. The latter stage of power flow is almost the same as wind power except for some control functions. Figure 4 shows the schematic diagram of solar power generation technology with its control layers. This technology depends on the two major parameters of weather, which are solar irradiance and ambient temperature. As the single solar cell produces very little power, the string of solar PV cells in series and parallel are used to set up a solar panel module. Such a single module can be capable of producing power in the order of KW. As a result, additional such modules are linked in series and parallel. The needs for PV-based solar power systems are increased power capacity compared to the wind power generators, health monitoring of panels, and power quality control on the grid side.

Considering all these requirements, different control techniques are classified, such as first layer, second layer, and third layer of control. The first layer of control is to control the variability of input power and deliver stable power on the grid side through MPPT, current/voltage, and grid synchronization. PV penalty monitoring, FRT, and power quality are complex controls of PV-based generation.

3. Desired protection coordination of green energy sources at distribution level

This section deals with desired coordination under any condition to improve continuity of supply to the consumer.

3.1. Desired OCR–OCR coordination

Generally, the LINKNET structure has been extensively applicable for OCR–OCR coordination. The LINKNET structure gives suitable primary and backup relay pairs at any given size of the network. Sympathetic tripping and wrong coordination are the concerns of OCR–OCR coordination.

3.2. Desired fuse to recloser coordination

For the 11 kV/415 V system, DO fuses (drop out fuses) and HRC fuses are widely used on the 415 V side of the transformer [14]. At 230 V, KitKat type fuses, MCBs, or RCBs are widely used. The relay and recloser are connected on the 11 kV side of the transformer. There is coordination required between the fuse and the recloser.

3.3. Desired fuse to fuse coordination

At 415 V and 230 V, fuses such as HRC and KitKat type fuses are respectively used. There is coordination required between fuses.

4. Challenges of integration in green technology

Miscoordination amongst the relays occur when there are changes in: 1. the location of distributed generation (DG), 2. the capacity of DG, and 3. the number of DG connected. This issue is further increased when fault resistance comes into consideration. Delays in operations are also perceived as undesirable. Apart from that, failure of the relay to operate may also be observed.

4.1. Coordination of fuse and auto recloser without Green Technology

As per the IEC standard, the total cycle which can be withstood by the circuit breaker of the power transmission line is the sum of the opening of the pole to 0.3 s of waiting time to closing time, followed by a second opening time to a 3-min delay and finally closing time. The advantage of an auto recloser is an instantaneous trip-out. Most of the faults are transient, and the recloser is operated first, saving the fuse. So it allows the fuse to blow only in the case of a permanent fault. Consider the distribution system shown in figure 5 where G1 is the traditional source of power through the substation, delivering power to the consumer. The bus-1 (busbar-1) has two transmission lines connected, which are called feeders. Feeder-2 has one line directly

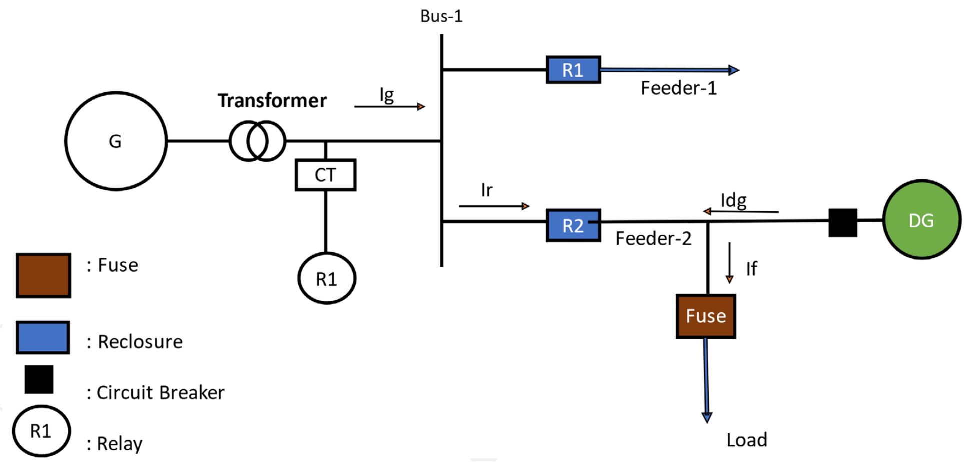

Figure 5. Fuse and recloser coordination under green energy resource integration in distribution system.

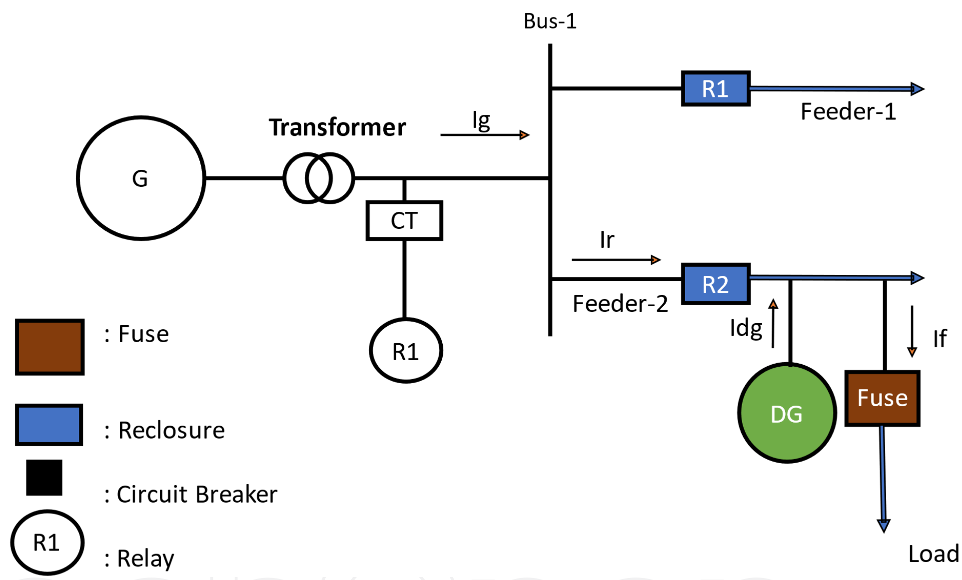

Figure 6. Fuse and recloser coordination under changed DG location.

taken, called laterals. This lateral is connected to the load using fuse-based protection while the feeder-1 and 2 have recloser based on current protection at the R1 relay.

The recloser-1 and 2 are shown in figure 5, which needed coordination with the fuse to save the fuse under transient fault conditions. This makes power continuity more reliable. When the system in figure 6 is considered without DG, the flow of current is from source to load, which enables this coordination correctly as first the recloser attempts and then the fuse attempts the fault. The characteristics of the recloser and fuse are well coordinated with the downstream flow of current. This is often called the "fuse-saving concept" [15].

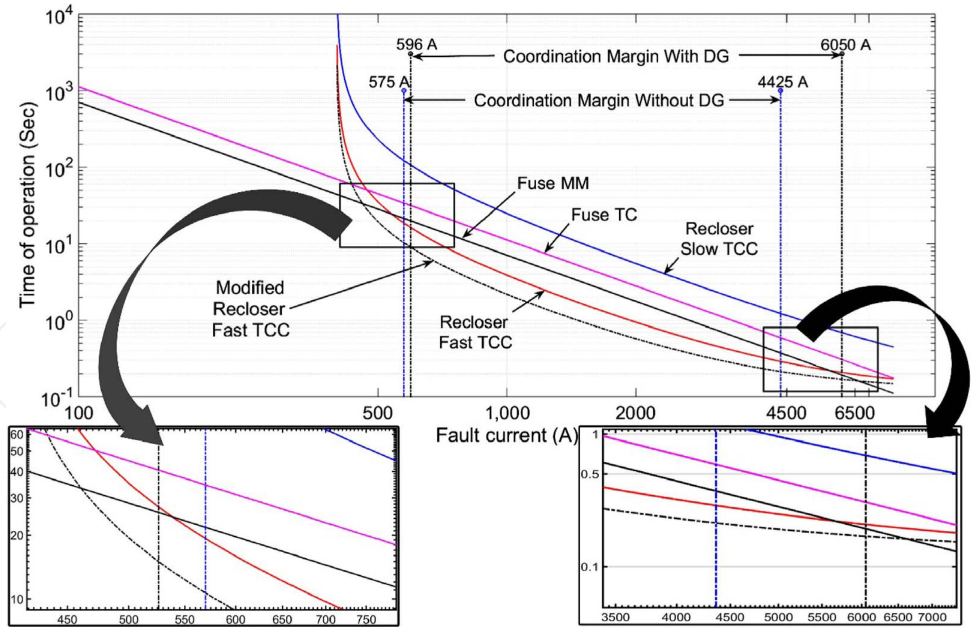

Figure 7. Fuse and recloser characteristics with and without DG in the distribution network.

4.2. Coordination of fuse and auto recloser with green technology

Now, if one considers DG based on green energy technology such as solar PV or wind, then power flow is bi-directional. Consider the transient fault on the load side in figure. Generally, as shown in figure 7, the recloser fast characteristic is below the fuse minimum melting characteristic under the minimum to maximum fault current to achieve the fuse saving concept. When the fault occurs, the current flow through the fuse is given by,

$$I_f = I_{dg} + I_r \tag{1}$$

where, I_r = current through recloser, I_{dg} = current feed by DG and I_f = current passing through the fuse.

Whereas the current through recloser is I_r. Now,

$$I_f > I_r. \tag{2}$$

From equations (1) and (2), it is clear that the fuse has a higher current than the recloser, which creates wrong coordination. The wrong coordination also depends on the amount of DG power and the type of DG.

5. Improvement in protection of distribution system

To overcome the issue derived in section 5, the proper margin is needed. As shown in figure 7, in the zoom part on the left side, the recloser curve is above the fuse curve near the minimum current value of 575 A to 596 A, without and with DG, and similarly at the side of maximum current. To overcome this issue, a new characteristic has been suggested with a dotted black line for recloser. The issue was bresolved by extending the recloser line as shown in figure 7. However, This is possible only up to a certain extent and not for all.

To achieve coordination in all ranges, the relation of the fault current from utility substation and the maximum or margin fault current from DG can be written as follows;

$$I_f = I_r + I_{\text{margin}}. \tag{3}$$

To ensure that the recloser will operate faster than the fuse, the fault current from DG must be lower than I_{margin}, which can be given by,

$$I_{\text{dg}} < I_{\text{margin}}. \tag{4}$$

6. Proposed solution considering optimization problem

The objective function f is to minimise the operating duration of auto recloser and fuse to assure a coordinated time interval (CTI) between the fuse and OC relays.

$$f(t_2, (t_2 - t_1)) = \min\left\{\frac{VC_n}{TC_n}\right\} + K1\left\{\frac{\sum_{n=1}^{TCn} t_1}{TC_n}\right\} + K2\left\{\frac{\sum_{n=1}^{TCn} t_2}{TC_n}\right\} + K3\left\{\sum_{ij=1}^{TCn} CTI_{ij}\right\} \tag{5}$$

where, t_1 = operating time of auto recloser, t_2 = fuse operating time, CTI = time interval between primary protection (fuse in this case) and back-up protection (auto recloser), $K1, K2, K3$ = weight factors for each term in equation (5), CTI_{ij} = Error in i–j path coordination time. Optimal weights were obtained by utilising the Pareto frontier.

$$\text{Fuse operating time } (t_2) = t_{\text{parc}} + t_{\text{arc}} \tag{6}$$

where, t_{parc} = pre-arcing time of fuse, and t_{arc} = arcing time of fuse.

The time grading required between auto recloser and fuse is given as [16],

$$\delta\left(t_2 - t_1\right) = 0.4t_2 + 0.15. \tag{7}$$

The operating time of recloser depends on overcurrent relay time, which is given as,

$$t_1 = \left[\frac{A}{\left(\frac{I_f}{\mathrm{PSM} \times I_L}\right)^x - 1} + B\right] \times \mathrm{TDS} \tag{8}$$

where TDS = time dial setting, I_f = maximum fault current, I_L = line load current to be protected, A, B, x are the curve setting parameters which decide the very inverse and extremely inverse settings, and PSM is the plug multiplier settings.

The constraint of the following optimization problem is as below,

$$\left((t_2 - t_1) \geq \mathrm{CTI}\right)_a \tag{9}$$

$$(\mathrm{PSM}_{\mathrm{min}} \leq \mathrm{PSM} \leq \mathrm{PSM}_{\mathrm{max}})_b \tag{10}$$

$$(\mathrm{TDS}_{\mathrm{min}} \leq \mathrm{TDS} \leq \mathrm{TDS}_{\mathrm{max}})_b \tag{11}$$

$$(t_2^{\mathrm{min}} \leq t_2 \leq t_2^{\mathrm{max}})_a \tag{12}$$

where a is the total number of auto-reclosers with fuse coordination and b, the total reclosers with overcurrent relay.

Equation (5) is optimised using a genetic algorithm (GA) for constants given by equations (9) to (11). The next section discusses the results.

7. Results and discussion

The figure 5 system is used for testing the proposed optimization solution. The implementation steps of GA for testing of the proposed optimization solution are given in this section. In the end, the results obtained are depicted and discussed.

7.1. Initialize the population

Chromosomes are a set of possible $[t_1, t_2]$ using standard equation (7) for fuse and relay R2 in figure 5. Here, $a = 1$ and $b = 2$ as the system is small. So, a total of $b^5 = 32$ chromosomes are generated.

7.2. Fitness calculation

For each chromosome, fitness is calculated using the objective function of equation (5). Now those chromosomes which give the minimum value of fitness function are selected. Here, selection is considered using a roulette wheel.

7.3. Crossover

From selected chromosomes, t_1 and t_2 are converted into binary values called genes for all selected sets of fitness.

7.4. Mutation

In this step, the genes are altered from pair to pair randomly. In the above case study, total genes are 48, so 5 genes are muted. So, five random values for row and column are chosen. Now the binary value of chromosomes is again converted into integer format and fitness is calculated. This process is repeated until one of the chromosomes satisfies the target minimum value considering all constraints. The line reactance of the feeder-2 is considered to be 0.371 Ω.

The system in figure 5 is simulated using PSCAD Trail version software to get the fault current through various points such as R2 , fuse, and grid side relay with and without DG. Table 1 depicts the results of load flow values. This value clearly shows that due to the high contribution of DG, current through R2 is reduced from its normal value without DG. The same issue is seen with grid side relay too. This incident results in the missing operation of the grid-side relay. Table 2 shows the result obtained with conventional fixed settings obtained from equation (7) with fixed settings of the overcurrent relay for recloser R2, which needs revision.

Table 1. Fault current value from recloser, fuse, and grid side relay with and without DG.

Recloser-Fuse		**I_f (A) Without DG**		**I_f (A) With DG**	
Primary	Backup	Primary	Backup	Primary	Backup
R2	Fuse	580.5	520.2	451.5	500.6
Grid side Relay	Fuse	650	520.2	470.5	500.6

Table 2. Coordination with the conventional method using equation (7) with DG operation.

Recloser-Fuse		**t_1 (s)**	**t_2 (s)**	**CTI (s)**
R2	Fuse	0.21	0.2	Failed
Grid side Relay	Fuse	0.32	0.3	Failed

The proposed system is solved considering optimization of t_1 and t_2 and $(t_2 - t_1)$ as discussed in this section initially. The results are shown in table 3, which clearly shows that proper CTI is maintained between the grid side relay, R2, and Fuse with DG connected. The proposed method gives an optimised value of PSM, TDS, A, B,

Table 3. Optimised value obtained from testing the proposed method with DG operation.

Auto recloser/ relay	TDS	PSM	A	B	x	t_1 (s)	t_2 (s)	CTI (s)
R1	0.60	1.5	6.80	0.2	1.82	1.354	3.0113	1.658
Grid side Relay	0.61	1.0	6.81	0.2	2.20	1.574	3.56	1.986

and x, which gives t_1 = 1.354 s and t_2 = 3.011 s for case-1, which is the correct operation. Similarly, for grid side relay and Fuse, the CTI obtained is 1.98 s, which is correct coordination.

8. Conclusion(s)

In this paper, the development of green energy technology has been highlighted initially with the help of IRENA data, which shows the higher growth rate of three main green energy technologies, which are wind energy, solar energy, and renewable hydro energy. The latest control of wind and solar has been discussed, which shows its limitations in terms of cost and protection issues. Considering solar and wind as DGs in the distribution network, it is narrated that the wrong coordination of fuses and reclosers in the distribution network depends on the size of DG, location of DG, and type of DG. To overcome this issue, a sufficient margin is required between recloser and fuse characteristics. The problem is more serious in a complex, large network. The problem is formulated in this work with equations (5) to (12) and solved using the genetic algorithm method for optimised value of recloser time and fuse time with grid side relay, considering the test system. The result obtained with the proposed method gives correct coordination with optimised values of PSM TDS, A, B, and x. However, the proposed optimization algorithm needs further validation on large-scale systems with a greater number of fuses and reclosers.

Conflict of interest

The authors declare no conflict of interest.

Appendices and Nomenclature

IRENA = International renewable energy agency

GES = Green Energy Sources

GA = Genetic Algorithm

MW = Mega Watt

CT = Current transformer

MCB = Miniature circuit breaker

RCB = Residual Circuit breaker

AC = Alternating Current

DC = Direct Current

IEC = International Electrotechnical commission

DO = drop out

PMSG = Permanent magnet Synchronous generator

PWM = Pulse with Modulation

DFIG = Doubly fed induction generator

HV = High Voltage

kV = kilovolt

FRT = Fault Ride through

DG = Distributed generator

OCR = Over current relay

PSM = Plug setting multiplier

TDS = time dial settings

PSCAD = power system computer aided design

I_r = current through recloser in Ampere

I_{dg} = current feed by DG in Ampere

t_1 = Operating time of auto recloser

t_2 = Fuse operating time

CTI = time interval between primary protection (fuse in this case) and back-up protection (auto recloser)

CTI_{ij} = Error in i–j path coordination time. Optimal weights were obtained by utilising the Pareto frontier.

I_f = current passing through the fuse in Ampere

I_{margin} = Margin level of current delivered by DG in Ampere

$K1, K2, K3$ = weight factors

t_{parc} = Pre-arcing time of fuse

t_{arc} = Arcing time of fuse.

a is the total number of auto-reclosers with fuse coordination

b = total reclosers with overcurrent relay.

θ = pitch angle in degree

ω = Rotational Angle in rad.

G = utility generation source

R1 = recloser 1

R2 = recloser 2

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