Ain Shams Engineering Journal 10 (2019) 379–388

Contents lists available at ScienceDirect

Ain Shams Engineering Journal

journal homepage: www.sciencedirect.com

Electrical Engineering

An advanced protection coordination technique for solar in-feed distribution systems

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ARTICLE INFO

Article history:
Received 1 January 2018
Revised 10 March 2019
Accepted 3 April 2019
Available online 22 April 2019

Keywords:
Distributed energy resources (DERs)
Voltage based time inverse over current relay characteristics
Solar in-feed distribution systems (DS)
Differential evolution algorithm (DEA)

ABSTRACT

Distributed electricity resources (DERs) are power generating sources which are installed to meet the increasing peak demand. Renewable and zilch emission characteristics are making them as a perfect choice in distribution system. But the designing of protection scheme for the fruitful operation of distribution system (DS) places a challenging task for power system engineers. As the population of the solar based electrical DERs increase in the electrical DS, the fault current contribution from these resources becomes comparatively less with the fault current from utility substation. In this research commentary, voltage and current based protection algorithm is offered which can accurately detect the fault current from solar in-feed DS. The proposed algorithm is implemented in IEEE 30 bus reference DS. The relay mis-coordination problem is solved by using differential evolution algorithm (DEA).

1. Introduction

Increasing energy demand is met by DERs. Renewable and zero emissions are the two important factor which suit for the selection of DERs. Still there are many technical challenges associated with the integration of DERs [1]. To ensure reliable, continuous and safe power supply to the end users, protection system is very much essential [2]. In [3] the effects of DERs in DS on the power system relay protection coordination (PC) are explained. The traditional power supply is by radial network with power supply at only one end. Designing of protection scheme for radial network is simple. For such network non-directional over current relays are predominantly used as the fault current contribution will be from one source [4]. Over current relays (OCRs) are the main and secondary protection elements in DS. The traditional protection scheme no longer suits the present DS. With the integration of more and more DERs local DS has converted to meshed network [5]. The fault current fed by DERs will be from multiple sides. The designing of PC for meshed network is very complex and calculations are tedious. For such network directional OCRs are predominantly used as the fault current contribution will be from multiple source [6–11]. For proper relay PC best possible relay settings (time dial settings-TDS & plug multiple settings-PMS) are very much essential. In traditional methods these settings are explored from hand calculations. PC problem for the standard time inverse over current relay is stated as linear optimization problem [12]. The relays operating time can be calculated easily. In simplex linear methodology only TDS are optimized and PMS are fixed at some value [13]. Many literatures are available for nonlinear programming techniques such as genetic algorithm [14], Ant colony algorithm [15], Modified Particle Swarm algorithm [16,17], Differential Evolution Algorithms (DEA) [18], Biogeography-Based Optimization Algorithm [19], Firefly algorithms [20], Covariance Matrix Adaptation Evolution Strategy Directed Target to Best Perturbation (CMAES-DTBP) [21] and Teaching Learning-Based Optimization (TLBO) Algorithm [22]. In [23] the PC problem with different type of non-linear algorithms (Genetic Algorithm (GA), Ant colony algorithm (ACA)), and (DEA) are discussed among them DEA is giving superior settings. DERs are mainly classified into two categories, synchronous based DERs and inverter based DERs. In synchronous based DERs the fault current contribution will be in the range of 4 to 6 times of rated current [24]. In inverter based DERs the fault current ranges from 1.5 to 2 times the rated current [26,27]. Even

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Peer review under responsibility of Ain Shams University.

Production and hosting by Elsevier

https://doi.org/10.1016/j.asej.2019.04.003
2090-4479/

though magnitude of fault current contribution is very much less in inverter based DERs their effects are predominately more than the synchronous based DERs [25]. Conventional characteristics equation is time-current inverse relay characteristics. Further studies are made to make the trip time minimum. A microprocessor based OCRs is developed as per today's technology is concerned. As the microprocessor based relay is user friendly relay characteristics equation can be reprogrammed easily. In [29] new logarithmic equation was proposed for OCR relay characteristics equation to make operating time minimum. A new nonstandard exponential characteristics equation that depend on current and also on voltage value for calculating relay in service time.

In this investigate article author introduces a logarithmic equation for voltage based over current relay model utilizes the voltage magnitude along with current magnitude to augment the working time of the relay. The standard time inverse relay model has two decision variables whereas voltage based over current relay has five decision variables. PC problem for the proposed voltage current time inverse OCRs characteristics is formulated as non-linear optimization problem. Non-linear constraints are constituted with five decision variables TDS, PMS, and Voltage pickup and relay constraints. The calculation of relay operating time is tedious as fault feeding is from multiple sources. To get into the bottom of this problem DEA is worn to attain the optimal relay settings for the anticipated relay model. To know the supremacy of proposed model is compared with literature method which is well thought-out as base paper [29] for this article work. This proposed voltage based OCR model uses the voltage level in p.u and fault current level in p.u for the relay PC problem formulation. This article is arranged into following sections as protection coordination problem formulation and results and discussion.

1.1. Standard time inverse relay model

Traditionally all networks are radial network as supply will be in one side. As the days evolved all radial network are getting converted into meshed network. Meshed network is nothing but to meet the peak demand integrating more number of generating sources into the network as a result network has changed to looped network. Generating sources includes solar, wind, biomass, bio fuel, geothermal etc. These are also called renewable energy resources or non-conventional energy resources. With the integration of both types of energy resources into generating section only, then transmission cost and transmission losses will be more. Hence to avoid these losses there is an integration of these energy resources directly to the DS. As they are connecting it to DS they are called distributed energy resources (DERs). To get continuous supply of electricity power system network has to be monitored continuously. This can be achieved by placing relays in the power system network. It is very difficult to design the relay in such a way that it will never fail so there should be a backup protection. Depending upon the location and the size of the network the number of backup relay will increase.

The in service time of the relays in standard time inverse relay model can be calculated by using Eq. (1).

$$\mathrm{T}^{\mathrm{i}}_{\mathrm{op}} = \mathrm{TDS_i} * \left[\frac{\alpha}{\left(\frac{I_{fault}}{I_{pickup}}\right)^{\beta} - 1} \right] \tag{1}$$

where,

$\mathrm{T}^{\mathrm{i}}_{\mathrm{op}}$ = Total in service time of all relays.

TDS = Time dial setting.

PSM = $\frac{I_{fault}}{I_{pickup}}$ Plug setting multiplier.

I_{fault} = Fault current level.

I_{pickup} = Pick up value of the relay current above which the relay should operate.

A and B = constants which depends on the relay characteristics.

The TDS used in Eq. (1) adjusts the time delay before the relay operates whenever the fault current reaches a value equal to, or greater than, the relay nominal current value.

1.2. Literature relay model

If the fault is nearer the source faster will be the relay action and vice versa. As the fault current contribution from the inverter based DERs is very less when compare to fault current contribution from the synchronous based DERs the relay will take more time to trip and sometimes relay mis-coordination will occur i.e backup relay will trip faster than primary relay. In the recent research article [29] the author has published a new time-current-voltage characteristics to overcome above mentioned problems.

The in service time of the relays in literature method can be calculated by using Eq. (2).

$$t_{pqr} = \left(\frac{1}{e^{1-v_{fpqr}}}\right)^{k} TDS \frac{A}{M_{pqr}^{B} - 1} \tag{2}$$

where,

$\mathrm{t_{pqr}}$ = in service time of relay (s) '*r*' due to a fault type '*q*' occurrence at location '*p*'.

$\mathrm{V_{fpqr}}$ = fault voltage magnitude (pu) calculated at relay '*r*' for a fault type '*q*' at location '*p*'.

M = Plug multiple settings (PMS).

K = constant term which is optimized between 0 and 3.

Further the authors [29] explains the reasons for considering above Eq. (2).

i. As the $\mathrm{V_f}$ varies with respect to fault location with respect to directional OCRs location at which it is measured.
ii. This $\mathrm{V_f}$ magnitude sometimes reaches zero. The exponential term is used to guarantee that operating time will not become zero when $\mathrm{V_f}$ magnitude is zero.
iii. The relay is designed in such a way that in service time is depends both on the voltage magnitude and current magnitude. A severe decrease in the voltage makes the relay to operate faster and vice versa. Thus the reciprocal of exponential term is considered $1 - \mathrm{V_{fpqr}}$
iv. If the $\mathrm{V_f}$ is zero, then this $\mathrm{V_f}$ can be vanished by setting K = 0. Then the in service time of the relay can be calculated by using standard time inverse relay model.
v. The exponential part which was chosen is such that it will not affect the TDS and PSM settings on relay characteristics.
vi. By considering this recent article a new equation has been proposed so that the relay will operate even faster by considering this fault voltage measurement. The last section results and discussion explains the superiority of new proposed relay model.

1.3. Proposed protection coordination problem formulation (pcpf)

As explained above, OCRs are primarily suits for the defense of radial electrical DS. The finest minimum probable relay in service time is achieved by using the relay PC problem as optimization complexity. The OCRs PC trouble is exceedingly non-linear in requisites of condition function and decision variables. The in service time of main OCRs can be calculated using Eq. (3)

$$T^{r}_{pri} = \left(\frac{\alpha * TDS}{\left(\frac{I_{fault}}{I_{pickup}}\right)^{\beta} - 1} \right) * \left(\frac{1}{1 - \log v^{M}_{\mathrm{pickup}}} \right)^{N} \tag{3}$$

where,

$\alpha\&\beta$ = constants which depends on the relay characteristics.

$V_{pickup}v_{pickup}$ = fault voltage magnitude (pu) calculated at relay.

$V_{pickup} = V_{fpqr.}$

M = constant term which is optimized between 1 and 3.

N = constant term which is optimized between 1 and 5.

M and N are optimized in order to reduce T^{r}_{pri}.

The condition function is distinct as summing up of the main OCRs in service time. The mathematical equation for the condition function is clear as according Eq. (4).

$$Z_{mod} = \min.\left[\left(A_1 * \sum_{p=1}^{n_p}\sum_{q=1}^{n_r}\left(Ts^{r}_{main}\right)^{L}\right)\sum_{p=1}^{M}(\text{Punishment})^{P}\right] \quad (4)$$

The mathematical equation for the penalty and error is according Eq. (5) and (6)

$$\text{Punishment} = \begin{cases} Error, \forall\Delta t_c < 0.3, \\ 0, \forall\Delta t_c \geq 0.3, \end{cases} \quad (5)$$

$$\text{Error} = A_2 * |0.3 - \Delta t_c|^2 * (\Delta t_c < 0.3) + B_1|\Delta t_c - 1.0|^2 * (\Delta t_c > 1.0) + Y \quad (6)$$

$$Y = B_1\left(Ts^{r}_{main} - 0.06\right) * \left(Ts^{r}_{main} < 0.06\right) \quad (7)$$

where, “r” denotes primary relay details for a fault at position “*p*”.n_r is total count of relays. n_p is the total count of fault position. Δt_c ″Δt_c″ is synchronization time edge, Ts_{main} is main relay in service time “q” for fault type at position “*p*”.B_1, A_2 & A_1 are the weighting factors for maintaining the operating constraints within the limits & to minimizing the total in service time of all main relays. “P” is the number of relays exceeding the synchronization time edge. M is the total count of relays exceeding the synchronization time edge.

1.4. Functioning constraints

The underneath mentioned constraints have to preserve the boundary conditions within the limits, if it exceeds the limits relay will not operate satisfactorily.

(i) *Margins on TDS setting:* The limits on time dial setting varies from 0.1 to 1.0.p.u. $TDS_{min} \leq TDS \leq TDS_{max.}$
(ii) *Margins on PSM setting:* The limits on plug multiple setting varies from 1.1 to 1.5.p.u
$PSM_{min} \leq PSM \leq PSM_{max.}$
(iii) *Margins on CTI:* The difference between the in service time of secondary and main relay is called CTI and it should be within 0.3 s.
T_s(Secondary) – T_s(Main)≥0.3 s.
(iv) *Margins on operating time*: The minimum operating time of main relay is 0.05 s.
Ts_{main}≥0.06 s.
(v) *Margins on constants M and N:* Constants M varies from 1 to 3 and N varies from 1 to 5.

Typically OCRs are first hand in the protection of DS. As the fault level feeding from synchronous machines is more, conventional OCRS can sense easily. But fault current level from solar in-feed power generating station is greatly pathetic limited by their inverter rating. As a result, process of OCRs becomes listless chiefly by the solar based power generating station. In this research article, the in service time of OCRs placed in a solar feed DS is improved by using a new-fangled relay representation, which respond quicker for a little increase in the terminal current and perceptible drop in bus voltage. The voltage based OCRs representation is compared with the present time inverse relay representation as per Table 1 beneath. In voltage based OCRs requires two input signals. Current signal is taken from current transformer (CT) and voltage signal is taken from potential transformer (PT). The current signal is small which results in late operation of relays. By providing the voltage signal to the relay in the voltage current time inverse OCR model the in service time is enhanced. By considering this voltage signal from PT, relay time is minimized. All relay in service time is adjusted by suitable variety of parameters M and N as stated in relay in service time equations.

During the normal periods the bus voltage will be in the nominal value of 1p.u whereas in the faulted periods the bus voltage will be decrease below 1p.u near to the DERs placement buses. Based on the decrease in voltage magnitude, voltage pickup is decided for each relay from the evolutionary optimization technique. As stated, in the voltage based OCRs mathematical equation of proposed method, with increase in fault current service time decrease and fall in bus voltage and hence named as voltage based OCRs in this editorial. The in service time is auxiliary improved by considering the exponential of M and N on the V_{pickup} of the relays in service time Eq. (3) in Table 1.

In the solar based linked electrical DS, whenever there is increase in the loading greater 1.1p.u to 1.5p.u which is considered as faulted condition. While these power generating sources are puny in environment and their bus voltage decrease under 0.9P.U. This raise in loading and fall in bus voltage is classified as in service region of the voltage based OCRs. Fault is detected by both main and secondary relays concurrently. To stay away from ill-operation of relay PC studies is very much essential, the secondary relay be supposed to trip only if main relay fails to operate due to some technical issues. If Re_i is the main OCRs for fault at *k* and Re_j is secondary OCRs of $Re_i$for the same fault, then the management of decision variable is stated as in Eq. (8)

$$t_{i,L} - t_{j,L} \geq \Delta t_c \quad (8)$$

where, $t_{i,L}$ is the in service time of the Re_j for fault at *L*; $t_{j,L}$ is the in service time for the Re_i for the same fault at *L*. Where t_c is known a synchronization time edge and is in general recognized as coordination time interval (*CTI).* Based on the experience of power system engineers CTI is selected in between 0.2 and 0.3 s. In proposed method CTI is chosen as 0.3 s

The proposed OCR PC problem is obtained with the assist of an evolutionary algorithm called DEA as shown in Fig. 1 and outcome are compared with further accurate technique.

Step by step procedure for DEA

i. Modify the constraints used in DEA coding which comprises greater & minor limits, inhabitants no. of relays used.
ii. Breed the carrier arbitrarily amid the known limits called goal vector.
iii. Compute the altered carrier by means of underneath produced goal vector.
iv. Altered carrier = Finest Goal carrier + F1*(Goal carrier2 -Goal carrier1).
v. In intersection it will match with altered carrier and goal carrier and produce recent trajectory carrier.
vi. If the punishments produced are zilch, dismisses or else step-3 replicates.

2. Results and discussion

2.1. Test system details

The test system considered in this research article is IEEE 30 bus electrical power DS. The details of network are reproduced below. Total numbers of generators considered are three which are

Table 1
Optimized relay settings for IEEE 30 bus distribution test system.

Relay no.	Standard time inverse relay		Proposed relay model				
	TDS	PSM	TDS	PSM	VP	M	N
1	0.1	1	0.14	2.5	0.8	3.5	3
2	0.13	1.5	1	0.5	0.5	5	1
3	0.23	2.5	0.61	2.5	0.1	2.5	1
4	0.12	1.5	0.42	1.5	0.7	3	1.9
5	0.1	0.5	0.16	2.5	0.7	4.5	2.3
6	0.12	1	0.76	0.5	0.4	2	1.2
7	0.55	0.5	0.47	1	0.9	3	1.5
8	0.24	1	0.3	1	0.3	1	1.3
9	0.3	2.5	1	0.5	0.8	2	2
10	0.11	1	1	1	0.1	1.5	1.1
11	0.47	0.5	0.46	2.5	0.6	1.5	1.5
12	0.1	2.5	0.24	1	0.1	1.5	1.5
13	0.43	2.5	0.97	0.5	0.8	1	1.1
14	0.5	0.5	0.29	2.5	0.9	4	1.1
15	0.86	2.5	1	2.5	0.8	5	1.2
16	0.37	2.5	0.5	2	0.8	1	1
17	0.37	1.5	0.58	1.5	0.8	4	1
18	0.3	1.5	1	0.5	0.2	1	3
19	0.1	1.5	0.18	2.5	0.4	1	3
20	0.25	1.5	0.8	0.5	0.8	2.5	2
21	0.73	0.5	0.99	1.5	0.8	1	2.8
22	0.26	0.5	0.1	2.5	0.9	1	1
23	0.62	0.5	0.93	1.5	0.3	1	1
24	0.1	0.5	0.96	1	0.5	3.5	2.7
25	0.46	2.5	0.76	1.5	0.9	4.5	1.1
26	0.87	1.5	0.48	2	0.9	3	1
27	0.46	1	0.59	1	0.7	3	1
28	0.18	2.5	0.78	1	0.5	1.5	2
29	0.19	2	0.6	2.5	0.7	4.5	2
30	0.24	2.5	0.51	2.5	0.5	2	1.2
31	0.21	2.5	0.5	1.5	0.6	2	1.4
32	0.34	1	0.68	1.5	0.6	5	1
33	0.25	2.5	0.63	2	0.8	3	3
34	0.43	0.5	0.27	2.5	0.8	2	1.2
35	0.98	2.5	0.82	0.5	0.7	3.5	3
36	0.21	2.5	0.54	2.5	0.2	4.5	1.2
37	0.44	0.5	0.61	2.5	0.6	5	1.1
38	0.25	2.5	0.77	2	0.5	1	2.4
39	0.12	2.5	0.57	1.5	0.5	2	2.1
40	0.24	0.5	0.28	1.5	0.6	2	2.1
41	0.21	2.5	0.47	2	0.5	2	1.1
42	0.18	1	0.42	2.5	0.1	3.5	2.3
43	0.21	2	0.41	2.5	0.7	2.5	1.9
44	0.14	2.5	0.13	2.5	0.4	1	1.9
45	0.1	0.5	0.14	0.5	0.3	2	1
46	0.15	2.5	0.29	1.5	0.8	2	1.6
47	0.1	0.5	0.14	2.5	0.3	3	1.1
48	0.38	0.5	0.89	1	0.4	1.5	1.7
49	0.28	2.5	0.95	1.5	0.7	5	1.9
50	0.18	2.5	0.68	1	0.5	1.5	1.3
51	0.26	0.5	0.7	2	0.8	4.5	2.7
52	0.3	1.5	0.82	2	0.7	3.5	1.6
53	0.1	0.5	1	2.5	0.3	3	2.8
54	0.76	0.5	0.49	2	0.8	1.5	1.5
55	0.1	0.5	0.25	0.5	0.3	5	1.1
56	0.4	2.5	0.65	0.5	0.8	1	1.9

connected to bus no.1, 2 and 18. The ratings of each generator are 50MVA, 35MVA, 12MVA respectively. The solo line diagram of IEEE 30 bus DS is as exposed in the Fig. 2. A part of DS is considered in IEEE 30 bus DS for the analysis purpose. The proposed method is analyzed by considering two cases. One is with DG incursion to the network another one is without DG incursion. The lines and generators information are in use from [28]. The DERs linked at bus 12 of 30 bus DS shown in Fig. 2. The rating of each generator is 50MVA, 35 MVA, 12 MVA connected to bus 2, bus 1 and bus 18 respectively in Fig. 2. The local micro-grid network which is connected in Fig. 3 is shown in sub figure of Fig. 2. Power stations are integrated at the bus 23 and 24. The micro grid system is created to check the performance of those relays which are fed power from solar based power station. The rating of each solar in-feed distribution power station is 12MVA which is represented in sub figure of Fig. 1. The solar based DS are connected to bus 23 and 24 as shown in Fig. 3. Total MVA in Fig. 3 is 12 + 12 = 24MVA, the total rating of generator is 100MVA i.e. 50MVA + 35MVA + 12MVA = 100MVA Therefore the total incursion level of solar based DS is 24/100 = 24%. As the power is fed from multi sources directional OCRs are installed at the each end of the lines. Without DERs 42 lines are considered and 44 relays are placed at the each end of the lines. With DERs 48 lines are considered and total 56 relays are installed at the each end of the lines. The in use path of each directional relays are noticeable in Fig. 2. The simulation results of proposed model are compared with conventional and literature method and results are tabulated. The buses 19, 20 and 21 are same in both Figs. 2 and 3. DERs is linked at bus 12 of IEEE 30 bus DS. Node 22, 23, 24 are extended system to connect the solar based DERs. The main objective is to analyze the performance of relays which are connected close to DERs, the nodal points 22, 23 and 24 are extended to analyze the performance of Re.53 to Re.56

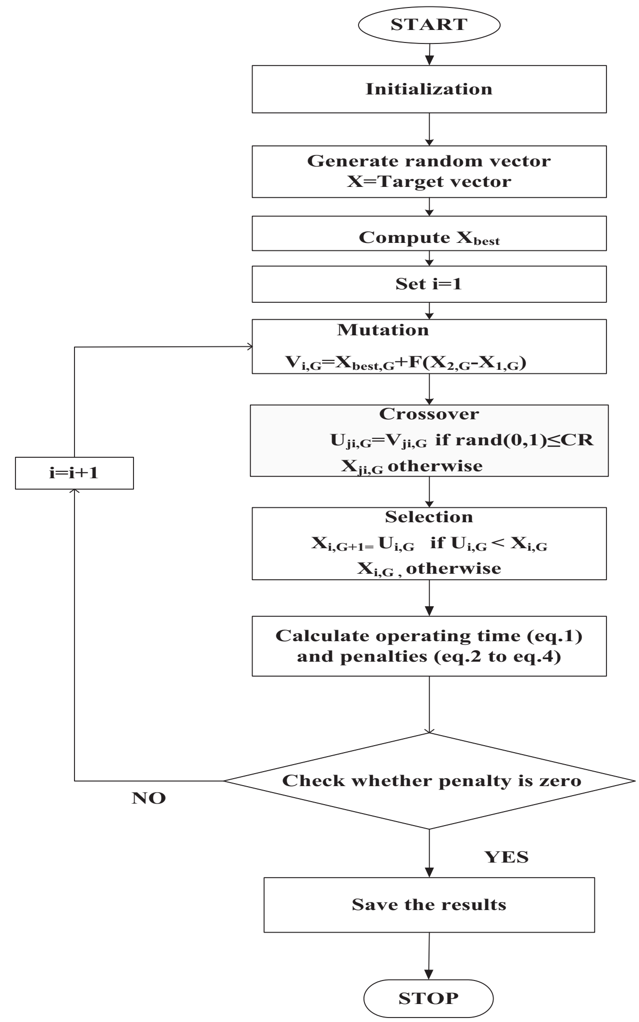

Fig. 1. Flow chart of relay in-service time calculation.

2.2. Simulation results

In this research article fault analysis is done exactly at the middle of the each line and the proposed method is verified for IEEE 30 bus electrical power DS with and without DG incursion. The

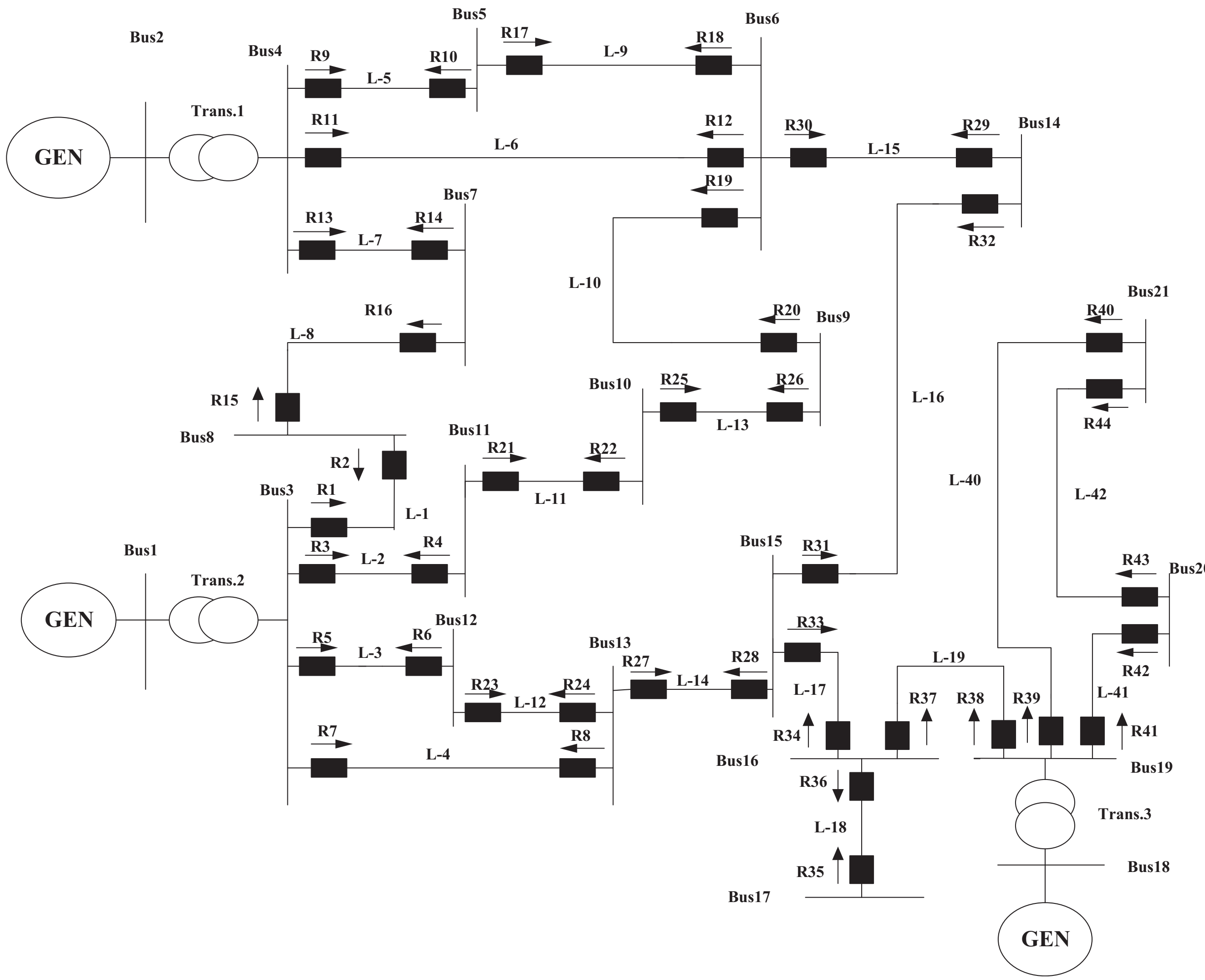

Fig. 2. IEEE 30 bus distribution system.

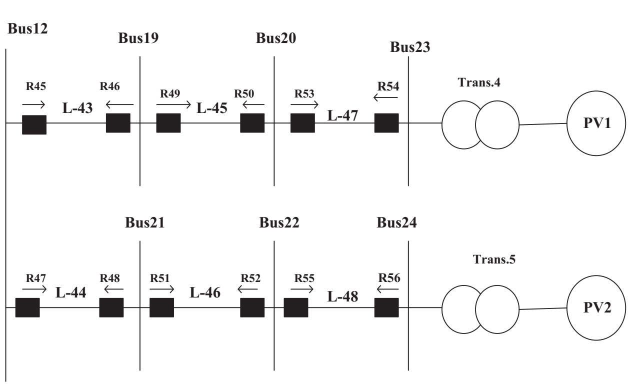

Fig. 3. Sub figure of Fig. 2.

simulation results are obtained by using DEA codes. DEA is used to optimize the relay settings and to maintain the PC between the main and secondary relay. In the standard time inverse relay model relay model two constraints TDS and PSM are optimized for all 56 relays with DG incursion at bus number 12. Likewise in proposed voltage based time inverse OCR along with standard time inverse relay model constraints three more constraints are used V_p, constant constraints M & N. These optimized constraints of all the 56 relays are scheduled in Table 1.

By using these optimized relay settings in service time of all the relays are calculated and tabulated. Table 2 represents the comparison of in service time of standard time inverse relay model and proposed relay model for the fault at the center of the transmission line section. In line L1 two directional relays are placed at the end of the each line which acts as primary relays (Re.1 & Re.2). Re.1 has two secondary relays (Re.6 & Re.8) and Re.2 has one secondary relay (Re.16). The number of secondary relays for the primary relay will varies based on the fault location. For few lines there will be multiple numbers of backups which is as listed in Table 2. It is observed that the relays (Re.46, Re.48, Re.50, Re.52) which are feeding fault current from the solar based power resources shows lethargic operation. The relay which are feeding fault current from solar based DERs will show sluggish operation as the magnitude of fault current from solar based DERs is very small, relay will take more time to trip. After implementing this logarithmic Eq. (3) the over all in service time is reduced. Their performance is enhanced with the assist of the logarithmic (proposed) relay model equation. The proposed Eq. (3) is named as logarithmic equation as the voltage magnitude considered is logarithmic value. The logarithmic values of voltage satisfy the current time inverse relay property.

Table 2
Comparision of operating time of relay in standard time and proposed methods for IEEE 30 bus distribution test system.

Fault at middle	Standard time inverse relay model			Proposed method		
	Ri,k = Ti,k (sec)	*Rj1,k = Tj1,k (sec)*	*Rj2,k = Tj2,k (sec)*	*Ri,k = Ti,k (sec)*	*Rj1,k = Tj1,k (sec)*	*Rj2,k = Tj2,k (sec)*
L-1	Re.1 = 0.188	Re.6 = 0.852	Re.8 = 1.074	Re.1 = 0.063	Re.6 = 0.898	Re.8 = 0.480
	Re.2 = 0.473	Re.16 = 0.792	–	Re.2 = 0.509	Re.16 = 0.815	–
L-2	Re.3 = 0.668	Re.8 = 1.561	Re.6 = 1.66	Re.3 = 0.262	Re.8 = 0.698	Re.6 = 1.260
L-3	Re.5 = 0.186	Re.2 = 0.608	Re.4 = 0.707	Re.5 = 0.06	Re.2 = 0.593	Re.4 = 0.621
L-4	Re.7 = 0.722	Re.2 = 1.1	Re.4 = 1.653	Re.7 = 0.477	Re.2 = 0.801	Re.4 = 1.452
	Re.8 = 0.378	Re.28 = 0.688	Re.23 = 1.126	Re.8 = 0.169	Re.28 = 0.47	Re.23 = 1.1
L-5	Re.9 = 0.675	Re.14 = 1.144	–	Re.9 = 0.683	Re.14 = 1	–
L-6	Re.11 = 0.749	Re.14 = 1.065	–	Re.11 = 0.514	Re.14 = 0.863	–
	Re.12 = 0.361	Re.29 = 0.694	Re.20 = 0.835	Re.12 = 0.061	Re.29 = 0.367	Re.20 = 0.709
L-7	Re.13 = 0.811	Re.10 = 1.13	–	Re.13 = 0.995	Re.10 = 1.987	–
	Re.14 = 0.802	Re.15 = 1.785	–	Re.14 = 0.522	Re.15 = 0.844	–
L-8	Re.16 = 0.707	Re.13 = 1.029	–	Re.16 = 0.733	Re.13 = 1.168	–
L-9	Re.17 = 0.672	Re.9 = 0.979	–	Re.17 = 0.577	Re.9 = 0.860	–
	Re.18 = 0.457	Re.20 = 0.988	Re.11 = 1.08	Re.8 = 0.067	Re.20 = 0.79	Re.11 = 0.832
L-10	Re.19 = 0.2	Re.29 = 0.874	Re.17 = 0.984	Re.19 = 0.06	Re.29 = 0.479	Re.17 = 0.815
	Re.20 = 0.649	Re.25 = 0.97	–	Re.20 = 0.596	Re.25 = 0.897	–
L-11	Re.22 = 0.477	Re.26 = 1.476	–	Re.22 = 0.3	Re.26 = 0.669	–
L-12	Re.24 = 0.154	Re.7 = 1	–	Re.24 = 0.064	Re.7 = 0.706	–
L-13	Re.25 = 0.885	Re.21 = 1.318	–	Re.25 = 0.829	Re.21 = 1.457	–
	Re.27 = 0.765	Re.7 = 1.088	–	Re.27 = 0.765	Re.7 = 1.088	–
L-14	Re.28 = 0.445	Re.34 = 0.882	–	Re.28 = 0.345	Re.34 = 0.706	–
L-15	Re.29 = 0.541	Re.46 = 0.888	Re.48 = 0.931	Re.29 = 0.278	Re.46 = 0.658	Re.48 = 0.672
	Re.30 = 0.64	Re.20 = 0.985	Re.11 = 0.96	Re.30 = 0.479	Re.20 = 0.788	Re.11 = 0.792
L-16	Re.31 = 0.606	Re.34 = 0.917	–	Re.31 = 0.441	Re.34 = 0.761	–
	Re.32 = 0.663	Re.48 = 0.986	Re.46 = 1.021	Re.32 = 0.424	Re.46 = 0.724	Re.48 = 0.726
L-17	Re.33 = 0.594	Re.32 = 0.903	Re.27 = 0.978	Re.33 = 0.297	Re.32 = 0.6065	Re.27 = 0.6061
	Re.34 = 0.78	Re.38 = 1.221	–	Re.34 = 0.564	Re.38 = 0.91	–
L-18	Re.36 = 0.55	Re.33 = 0.855	Re.38 = 1.533	Re.36 = 0.112	Re.33 = 0.416	Re.38 = 1.11
L-20	Re.39 = 0.508	Re.37 = 1.19	–	Re.39 = 0.294	Re.37 = 1.151	–
	Re40 = 0.877	Re.43 = 1.224	–	R40 = 0.567	Re.43 = 0.878	–
L-21	Re.41 = 0.681	Re.40 = 1.016	Re.37 = 1.135	Re.41 = 0.528	Re.37 = 1.015	Re.40 = 0.844
	Re.42 = 1.02	Re.44 = 1.372	–	Re.42 = 0.06	Re.44 = 0.37	–
L-22	Re.43 = 0.722	Re.41 = 1.062	–	Re.43 = 0.474	Re.41 = 0.783	–
	Re.44 = 0.638	Re.39 = 1.016	–	Re.44 = 0.172	Re.39 = 0.476	–
L-23	Re.45 = 0.153	Re.48 = 0.978	Re.31 = 0.887	Re.45 = 0.062	Re.48 = 0.718	Re.31 = 0.597
	Re.46 = 0.662	Re.50 = 0.976	–	Re.46 = 0.531	Re.50 = 0.841	–
L-24	Re.47 = 0.153	Re.31 = 0.887	Re.30 = 0.925	Re.47 = 0.064	Re.30 = 0.692	Re.31 = 0.597
	Re.48 = 0.812	Re.52 = 1.155	–	Re.48 = 0.563	Re.52 = 1.033	–
L-25	Re.50 = 0.826	Re.54 = 1.789	–	Re.50 = 0.76	Re.54 = 1.458	–
L-27	Re.53 = 0.227	Re.49 = 1.202	–	Re.53 = 0.069	Re.49 = 0.44	–
L-28	Re.55 = 0.210	Re.51 = 0.548	–	Re.55 = 0.061	Re.51 = 0.402	–

To check the superiority of the proposed (logarithmic Eq. (3)) model with the standard time inverse relay model the % change in service time is calculated and tabulated in Table 3. The % change in the service time of main and secondary relay is as shown in underneath for various fault location. However in few relays Re.2, Re.6, Re.9, Re.10, Re.13, Re.16, Re.21where there is deterioration in service time due to re-distribution of fault current among the relays. By using these relay settings in service time of the relays is calculated with and without DG incursion. The relays (Re.45 –Re.52) come into existence when DERs is connected to the original IEEE 30 bus electrical power DS at bus 12. Except few relay pairs which is mentioned earlier the remaining pairs shows appreciable reduction in service time. The relay pairs Re.45, Re.47 and Re.49 shows the predominant enhancement in service time.

Main agenda is to minimize the in service time of the relay which are feeding fault current from the solar in feed power DS. This is appreciably satisfied by using logarithmic Eq. (3). The proposed Eq. (3) is named as logarithmic equation as the voltage magnitude considered is logarithmic value. The logarithmic values of voltage satisfy the current time inverse relay property. The performance of relay is also enhanced.

Table 4 primary relay in service time is tabulated for all the 3 models (standard time inverse relay model, literature relay model, proposed relay model) when the fault is conducted at the middle of the section.

The relay pairs Re.16, Re.27, Re.43 are not tripping in the literature model are tripping at faster rate when compared to standard time inverse relay model and literature model.

As the author focus is to minimize the in service time of all primary relay especially the relay which are facing fault currents from solar based power system Table 5 is tabulated. In service time of all the main OCRs are tabulated in Table 5 and the comparison of all the three models (standard time inverse relay model, literature relay model, proposed relay model) are carried out. To know the superiority of the proposed method when compared to literature method and conventional method % change in service time is calculated and tabulated. In Table 5 first 10 relays (Re.45 to Re.56) are feeding fault current from solar system which have shown maximum % increase in the service time.

Main agenda is to make the relay more sensible in order to sense the low fault current which is fed by solar in feed DS. Even though the magnitude of fault current fed by solar in feed DS is small, but cannot be neglected. If the low magnitude fault current is feeding continuously then it affect the complete DS. From the Table 5 the maximum number of pairs show shrinks in service time when compared with standard time inverse relay model and literature relay method.

Table 3
Improvement in operating time of relay with proposed relay model for IEEE 30 bus distribution test system.

Relay no.	Operating time (s)				% Change in operating time	
	Standard time inverse relay model		Proposed relay model			
	Primary	Backup	Primary	Backup	Primary	Backup
45	0.153	0.175	0.062	0.071	59.47	59.42
46	0.662	0.888	0.531	0.658	19.78	25.9
47	0.153	0.175	0.064	0.079	58.16	54.85
48	0.812	0.986	0.563	0.726	30.66	26.36
49	0.857	1.202	0.376	0.44	56.12	63.39
50	0.826	0.976	0.76	0.841	7.99	13.83
51	0.493	0.458	0.336	0.402	31.84	12.22
52	1.022	1.155	0.891	1.033	12.18	10.56
1	0.188	0.23	0.063	0.08	66.48	65.21
2	0.473	0.608	0.509	0.593	−7.6	2.467
3	0.668	0.861	0.262	0.338	60.77	60.74
5	0.186	0.204	0.06	0.071	67.74	65.19
6	0.521	1.66	0.653	1.26	−25.3	24.09
7	0.722	1	0.477	0.706	33.93	29.4
8	0.378	1.567	0.169	0.698	55.29	55.45
9	0.675	0.979	0.693	0.86	−2.7	12.15
10	0.266	1.13	0.467	1.987	−75.6	−75.8
11	0.749	1.08	0.514	1	31.37	7.4
12	0.361	1.62	0.061	0.13	83.1	91.97
13	0.811	1.029	0.995	1.168	−22.7	−13.5
14	0.802	1.144	0.522	1	34.91	12.58
15	1.51	1.785	0.712	0.844	52.84	52.71
16	0.707	0.792	0.733	0.815	−3.7	−2.9
17	0.672	1.17	0.577	0.966	14.13	17.43
18	0.457	0.579	0.067	0.081	85.33	86.01
19	0.2	0.228	0.06	0.069	70	69.73
20	0.649	0.988	0.596	0.79	8.16	20.04
21	1.277	1.318	1.393	1.457	−9.1	−10.5
22	0.477	0.528	0.3	0.47	37.1	10.98
23	0.807	1.126	0.708	1.1	12.26	2.3
24	0.154	0.079	0.064	0.069	58.44	12.65
25	0.885	0.97	0.829	0.897	6.32	7.52
26	1.434	1.476	0.645	0.669	55.02	54.67
27	0.765	0.978	0.765	0.605	0	38.13
28	0.445	0.688	0.345	0.47	22.47	31.68
29	0.541	0.694	0.278	0.367	48.61	47.11
30	0.64	0.974	0.479	0.728	25.15	25.25
31	0.606	0.887	0.441	0.597	27.22	32.69
32	0.663	0.903	0.424	0.606	36.04	32.89
33	0.594	0.855	0.297	0.416	50	51.34
34	0.78	0.882	0.564	0.706	27.69	19.95
37	0.917	1.19	0.634	1.15	30.86	3.36
38	0.961	1.221	0.74	0.91	25.47	25.47
39	0.508	1.016	0.294	0.476	42.12	53.14
40	0.877	1.016	0.567	0.844	35.34	16.92
41	0.681	1.062	0.528	0.783	22.46	26.27
42	1.02	0.842	0.06	0.062	94.11	92.63
43	0.722	1.224	0.474	0.878	34.34	28.26
44	0.638	1.372	0.172	0.37	73.04	73.03

The performance analysis is carried out in Table 6 by considering the condition function in standard time inverse relay model, literature relay model and proposed relay model for Fig. 2.

To analyze the functioning time features of the relay primary relay in service time is plotted with fault current. In Fig. 3 comparison of CTI and main relay in service time of standard time inverse relay and proposed relay model are plotted for the fault at the center of transmission line for main relay Re.48 and secondary relay Re.52. The fault current sensed by the Re.48 and Re.52 is plotted with respect to in service time taken by those relay pairs. The CTI of relay pairs computed from proposed model is well optimized compared to conventional model.

In Fig. 4 the fault current identified by main Re.48 is 1787A and their corresponding in service time in conventional, literature, proposed model is 0.812 s, 0.644 s, and 0.563 s respectively. Fig. 4 shows the comparison of all the three relay model i.e standard time inverse relay model and literature relay model, with the proposed relay model. Fig. 4 shows the superiority of the proposed model. (See Fig. 5).

The fault current contribution is more in the synchronous based DERs when compare to inverter based DERs. This proposed voltage-current based inverse relay model works satisfactorily for synchronous based DERs also.

3. Conclusion

In service time of traditional OCRs feed with solar based DERs is tremendously deprived due to their low fault magnitude level. In this investigate article, the in service time of OCRs is improved by proposing an additional voltage based time inverse

Table 4
Comparision of operating time of Relay in all three methods for IEEE 30 bus distribution test system.

Fault at middle	Primary relay operating time (s)			Fault at middle	Primary relay operating time(s)		
	Standard time inverse relay model	Literature method	Proposed method		Standard time inverse relay model	Literature method	Proposed method
L-1	Re.1 = 0.188	Re.1 = 0.063	Re.1 = 0.063	L-15	Re.29 = 0.541	Re.29 = 0.507	Re.29 = 0.278
	Re.2 = 0.473	Re.2 = 0.378	Re.2 = 0.509		Re.30 = 0.64	Re.30 = 0.562	Re.30 = 0.479
L-2	Re.3 = 0.668	Re.3 = 0.337	Re.3 = 0.262	L-16	Re.31 = 0.606	Re.31 = 0.645	Re.31 = 0.441
L-3	Re.5 = 0.186	Re.5 = 0.206	Re.5 = 0.06		Re.32 = 0.663	Re.32 = 0.678	Re.32 = 0.424
L-4	Re.7 = 0.722	Re.7 = 0.311	Re.7 = 0.477	L-17	Re.33 = 0.594	Re.33 = 0.521	Re.33 = 0.297
	Re.8 = 0.378	Re.8 = 0.291	Re.8 = 0.169		Re.34 = 0.78	Re.34 = 0.81	Re.34 = 0.564
L-5	Re.9 = 0.675	Re.9 = 0.671	Re.9 = 0.683	L-18	Re.36 = 0.55	Re.36 = 0.377	Re.36 = 0.112
L-6	Re.11 = 0.749	Re.11 = 0.566	Re.11 = 0.51	L-20	Re.39 = 0.508	Re.39 = 0.259	Re.39 = 0.294
	Re.12 = 0.361	Re.12 = 0.146	Re.12 = 0.06		Re.40 = 0.877	Re.40 = 0.518	Re.40 = 0.567
L-7	Re.13 = 0.811	Re.13 = 0.341	Re.13 = 0.99	L-21	Re.41 = 0.681	Re.41 = 0.097	Re.41 = 0.528
	Re.14 = 0.802	Re.14 = 0.551	Re.14 = 0.52		Re.42 = 1.02	Re.42 = 0.08	Re.42 = 0.06
L-8	Re.16 = 0.707	Re.16 = not tripping	Re.16 = 0.73	L-22	Re.43 = 0.722	Re.43 = not tripping	Re.43 = 0.474
L-9	Re.17 = 0.672	Re.17 = 0.614	Re.17 = 0.57		Re.44 = 0.638	Re.44 = 0.209	Re.44 = 0.172
	Re.18 = 0.457	Re.18 = 0.360	Re.18 = 0.06	L-23	Re.45 = 0.153	Re.45 = 0.507	Re.45 = 0.062
L-10	Re.19 = 0.2	Re.19 = 0.122	Re.19 = 0.06		Re.46 = 0.662	Re.46 = 0.763	Re.6 = 0.531
	Re.20 = 0.649	Re.20 = 0.499	Re.20 = 0.59	L-24	Re.47 = 0.153	Re.47 = 0.187	Re.47 = 0.064
L-11	Re.22 = 0.477	Re.22 = 0.571	Re.22 = 0.3		Re.48 = 0.812	Re.48 = 0.644	Re.48 = 0.563
L-12	Re.24 = 0.154	Re.24 = 0.104	Re.24 = 0.06	L-25	Re.50 = 0.826	Re.50 = 0.962	Re.50 = 0.76
L-13	Re.25 = 0.885	Re.25 = 0.73	Re.25 = 0.82	L-27	Re.3 = 0.227	Re.53 = 0.092	Re.53 = 0.069
	Re.27 = 0.765	Re.27 = not tripping	Re.27 = 0.76	L-28	Re.55 = 0.210	Re.55 = 0.063	Re.55 = 0.061
L-14	Re.28 = 0.445	Re.28 = 0.606	Re.28 = 0.34				

Table 5
Improvement in operating time of relay with proposed relay model and literature method for IEEE 30 bus distribution test system.

Relay no.	Operating time (s) of primary relays			% Change in operating time		Relay no.	Operating time (s) of primary relays			% Change in operating time	
	Standard time inverse relay model	Literature relay model	Proposed relay model	Literature relay model	Proposed relay model		Standard time inverse relay model	Literature relay model	Proposed relay model	Literature relay model	Proposed relay model
45	0.153	0.507	0.062	−231.3	59.47	17	0.672	0.804	0.577	−19.6	14.13
46	0.662	0.763	0.531	−13.23	19.78	18	0.457	0.36	0.067	21.22	85.33
47	0.153	0.187	0.064	−22.22	58.16	19	0.2	0.122	0.06	39	70
48	0.812	0.644	0.563	20.68	30.66	22	0.477	0.571	0.3	−19.7	37.1
50	0.826	0.962	0.76	−1.85	7.99	24	0.154	0.104	0.064	32.46	58.44
51	0.493	0.41	0.336	16.84	31.84	26	1.434	0.885	0.645	38.28	55.02
53	0.227	0.09	0.069	60.35	69.6	27	0.765	1.066	0.765	−39.34	0
54	1.46	1.38	1.026	5.47	29.73	28	0.445	0.606	0.345	−36.11	22.47
55	0.21	0.061	0.06	70.95	71.43	29	0.541	0.507	0.278	6.28	48.61
56	1.29	1.23	0.801	4.6	37.91	30	0.64	0.562	0.479	12.18	25.15
1	0.188	0.063	0.06	66.48	68.09	31	0.606	0.645	0.441	−6.43	27.22
3	0.668	0.337	0.262	49.55	60.77	32	0.663	0.678	0.424	−2.26	36.04
5	0.186	0.206	0.06	61.82	67.74	33	0.594	0.521	0.297	12.28	50
8	0.378	0.291	0.169	23.01	55.29	34	0.78	0.81	0.564	−3.48	27.69
11	0.749	0.566	0.514	24.43	31.37	38	0.961	0.974	0.74	−1.35	25.47
12	0.361	0.146	0.061	59.55	83.1	42	1.02	0.08	0.06	92.15	94.11
14	0.802	0.551	0.522	31.29	34.91	43	0.722	0.586	0.474	18.84	34.34
15	1.51	1.14	0.712	24.5	52.84	44	0.638	0.209	0.172	67.24	73.04

Table 6
Condition function for IEEE 30 bus DS.

Condition Function (s) Standard time inverse relay model	Literature relay model	Proposed relay model	% Reduction Literature relay model	Proposed relay model
26.66 s	15.94 s	14.46 s	40.21%	45.76%

functional to conventional time-inverse over current relay characteristics. With the increase in the network complexity the overall operating time taken by the relay is also increased. Thus to increase the performance of all the relays and especially the relay which is fed by the solar based system the voltage based OCRs characteristics implemented in this editorial. Also hereby conclusion can be drawn as by considering the logarithmic function rather than exponential function the in service time is decreased and performance is improved in terms of their operating time.

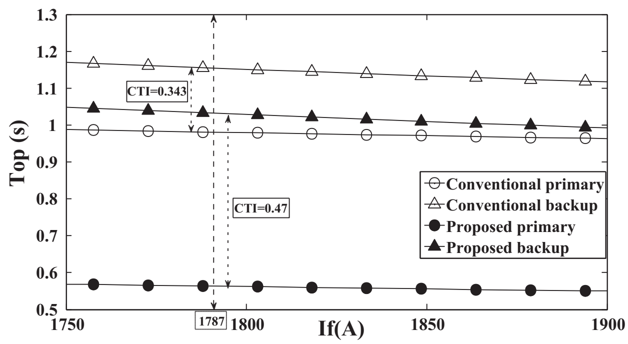

Fig. 4. Functioning time features of Re.48 and Re.52 in IEEE 30 bus electrical distribution test system.

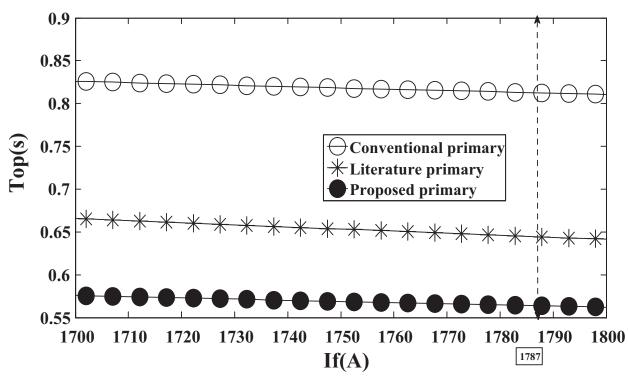

Fig. 5. Working time features of Re.48 in IEEE 30 bus distribution electrical test system.

Acknowledgement

There are no funding sources for this work, and all the authors are declaring that they do not have any conflict of interests.

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