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Protection Algorithm for Photovoltaic Based Distribution System

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Distributed Energy Resources (DERs) are small size power generating sources installed to electricity requirement of small scale electricity customers. Zero emission and renewable feature make them as popular choice for future energy demand particularly in peak demand in public utility network. The design of a protection scheme for their safe operation during utility tied connection and islanded mode of operation is an essential operational requirement. As the density of the photovoltaic based distributed energy resources increase in the distribution systems, the fault current contribution from these resources becomes comparable with the fault current from utility substation. Additionally the fault infeed for PV system is close to their loading limits and this possesses a great challenge for design of protection schemes. In this research article, a voltage and current based protection algorithm is presented which can accurately discriminate between the fault currents seen during utility tied and islanded mode of operation. The proposed algorithm is implemented in IEEE 9 bus reference network.

Keywords: *Distribution energy resources, Photovoltaic, Voltage-current time inverse relay characteristics and distribution system*

1.0 INTRODUCTION

Protection is an important element of power systems for their safe and reliable operation [1]. To provide reliable electric power supply to the customers, distribution systems are designed as meshed networks. Rising energy electricity demand may be met with the help of distributed renewable energy resources. Low emission and renewable nature are two key driving features for their fast integration in the power utilities [2]. These are distributed in nature and known as Distributed Energy Resources *(DERs)* and are generally placed near the consumer loads and do not require the large transmission. Conventionally most of distribution networks are radial network with main supply atone end and loads will be at other end. For radial network fault current contribution will be from main source, therefore nondirectional over current relays are predominantly used for protection of radial distribution systems. Local integration of DERs in distribution systems results in

Inter-connection and bidirectional flow of load as well as fault current during normal and fault periods respectively. The conventional protection schemes are designed for unidirectional flow of fault current no-longer valid for protection of interconnected distributed systems.In the literature, attempts have been made to control the impact of fault level from Distributed Energy Resources (DER) [4]. These include either the application of fault current limiter to block the fault current from DER or disconnecting the DER during the faults [5]. Some papers discussed about localizing the DER impact in the local area rather than spreading it towards the upstream transmission side. These techniques are quite helpful for low penetration level of DERS

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in distribution systems [6]. However, as the penetration level of distributed RES is increasing, a more robust protection scheme is required which can maintain the protection coordination during large scale penetration of DERs [7].

Presently penetration of photovoltaic based DER is rapidly increasing in India as well as in abroad. These power generating resources have limited fault feeding capabilities due to their inverter rating limitation as compare to the synchronous machines [8]. When these power generating resources are connected at remote end of utilities, weak fault current sensed by over current, which are originally set to operate for high upstream fault currents. Under these scenario, the over current relay based protection coordination scheme fails to discriminate between weak fault current and over load current infeed from the photovoltaic based system [9-10]. A new relay model is proposed which utilizes the voltage and current signal to enhance the operating time of the relay. The proposed relay model have five variables as compare to standard time inverse over current relay which has only time dial setting(TDS) and plug setting(PS) parameters[11]. The proposed relay model requires the nodal voltage and fault current as two inputs. The operating time of proposed relay is non-linear in nature and relay coordination problem is formulated as optimization problem. Differential evolution algorithm (*DEA*) is used to obtain the optimal relay settings for the proposed relay model [12]. This article is organized as introduction, problem formulation and results and discussion.

2.0 PROTECTION COORDINATION PROBLEM FORMULATION

As discussed above, over current relays are predominately used for the protection of radial distribution systems. The best minimum possible operating time is obtained by solving the relay coordination problem as optimization problem. The relay coordination problem is highly non-linear in terms of fitness function and constraints sets. The fitness function is defined as summation of operating time of the primary over current relays. The mathematical expression for the fitness function is defined as per eq (1).

$$J_{mod} = \min.\left[\left(\alpha_1 * \sum_{k=1}^{FL}\sum_{i=1}^{N_r}(T_{pri}^{i})^{k}\right)\sum_{p=1}^{M}(Penalty)^{P}\right] \quad ..(1)$$

$$Penalty\begin{cases} EV, & \forall\, \Delta t_{mb} < 0.3\,, \\ 0, & \forall \Delta t_{mb} \geq 0.3, \end{cases} \quad ...(2)$$

$$EV = \alpha_2 * |0.3 - \Delta t_{mb}|^2 * (\Delta t_{mb} < 0.3) + \beta_1 * |\Delta t_{mb} - 1.0|^2 * (\Delta t_{mb} > 1.0) + Z \quad ...(3)$$

$$Z = \beta_2(T_{pri}^{i} - 0.06) * (T_{pri}^{i} < 0.06) \quad ...(4)$$

Where,"i^{th}"denote primary relay notation for a fault at location "*k*". N_r is number of relays. $(T_{pri})^k$ is operating time of primary relay "i" for fault at location "*k*" .

Mostly distribution systems are protected by over current relays and their operating time is adequate due to high fault current feed from the synchronous machines. But fault feeding capabilities of PV based power stationis highly weak limited by their inverter rating. Therefore, operation of over current relay becomes highly sluggish particularly when they are only fed from the PV based power sources. In this research article, the operating time of relay installed in a PV feed distribution system is enhanced by proposing a new mathematical relay model, which operates faster for a small rise in the load current and noticeable fall in nodal voltage. The proposed relay model is compared with the existing time inverse relay model as per Table I below. In the proposed relay model the input signal are taken from current transformer (CT) and potential transformer (PT). The CT signal is small rise in load current during fault and this results in sluggish operating time of installed over current relays. This is enhanced by feeding the voltage signal to the relay in the proposed relay model.Operating time performance is tuned by proper selection of variable A and Z as mentioned in relay model equation for the proposed relay model in Table.1

TABLE 1

COMPARISON BETWEEN LITERATURE METHOD AND PROPOSED METHOD

S. No	Description	Literature relay model (Time inverse over current relay)	Proposed relay model (Voltage current time inverse relay)
1.	Relay Model- operating time equation	$T_{pri}^{i} = TDS_i * \left[\frac{\alpha}{\left(\frac{I_{fault}}{I_{pickup}}\right)^{\beta} - 1}\right]$	$T_{pri}^{i} = \left(\frac{\alpha * TDS}{\left(\frac{I_{fault}}{I_{pickup}}\right)^{\beta} - 1}\right) * \left(\frac{1}{1 - log v_{pickup}^{A}}\right)^{Z}$
2	No. of decision variables	Two(TDS and v_{pickup})	Five (TDS, v_{pickup}, v_{pickup}, A and Z)
3	Time dial setting (TDS)	Varies from 0.1 to 1.0	Varies from 0.1 to 1.0
4	Current Pickup (v_{pickup})	Varies from 1.5% of loading to 2/3rd of line to line current	Varies from 1.1% to 150% of loading
5	Voltage Pickup (v_{pickup})	--	Should be less than 0.9 P.U
6	A	--	1.0 to 3.0
7	Z		1.0 to 5.0
8	Relay characteristics	Standard time inverse relay	User defined.

During the fault periods, the nodal voltage mostly falls below 1.0 p.u near the DER point of common coupling and this information is fed to the relay through the PT. Based on the fall of voltage near the relay during the fault period, the voltage pickup is decided for each relay from the optimization algorithm. As mentioned, in the proposed mathematical expression of proposed relay model, the operating time is inversely proportional to the rise in current and falls in nodal voltage and hence termed as voltage current time inverse over current relay. The operating time is further enhanced by computing the operating time with power of A on v_{pickup} and Z on the voltage inverse term of the operating time expression in operating time expression in Table 1. Z and A are optimally chosen between 1 to 5 and 1 to 3 respectively.

In the PV based connected distribution system, whenever there is increase in the loading more than 110% of the nominal loading it is classified as fault condition. Since these power sources are weak in nature and their nodal voltage falls below 0.9 P.U. The intersection of rise in current and fall in nodal voltage below 0.9 P.U is classified as operating region of the proposed relay. The operating time region of the proposed voltage current time inverse relay is marked in Figure 1 below.

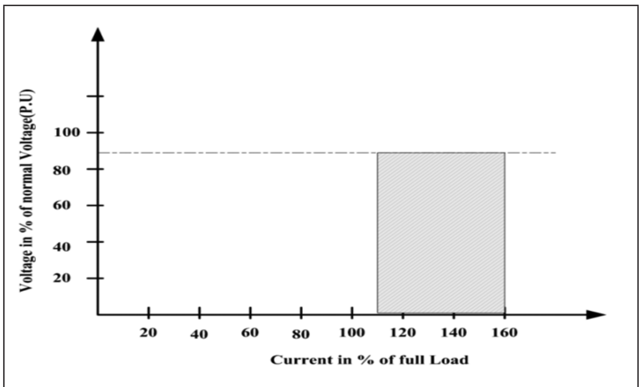

FIG.1 OPERATING REGION OF PROPOSED RELAY

2.1 Selectivity Constraint

Fault is sensed by both primary as well as backup over current relays simultaneously. To avoid mal-operation in the over current relay coordination studies, the backup over current relay should trip only if primary over current relay fails to trip. If R_i is the primary relay for fault at k and R_j is backup relay of R_i for the same fault, then the coordination selectivity constraint is stated as;

$$t_{j,k} - t_{i,k} \geq \Delta t_{mb} \quad ...(5)$$

where, $t_{j,k}$ is the operating time of the R_j for fault at k; $t_{i,k}$ is the operating time for the R_i

for the same fault at *k*. Where Δt_{mb} is known as coordination time margin and is commonly known as coordination time interval (*CTI)*. In the proposed relay over current coordination problem it is taken as 0.3 sec.

The proposed relay coordination problem is solved with the help of an evolutionary algorithm [13] and results are compared with other exact method. The sequence of solution of the proposed non-linear relay coordination problem is explained in Figure 2.

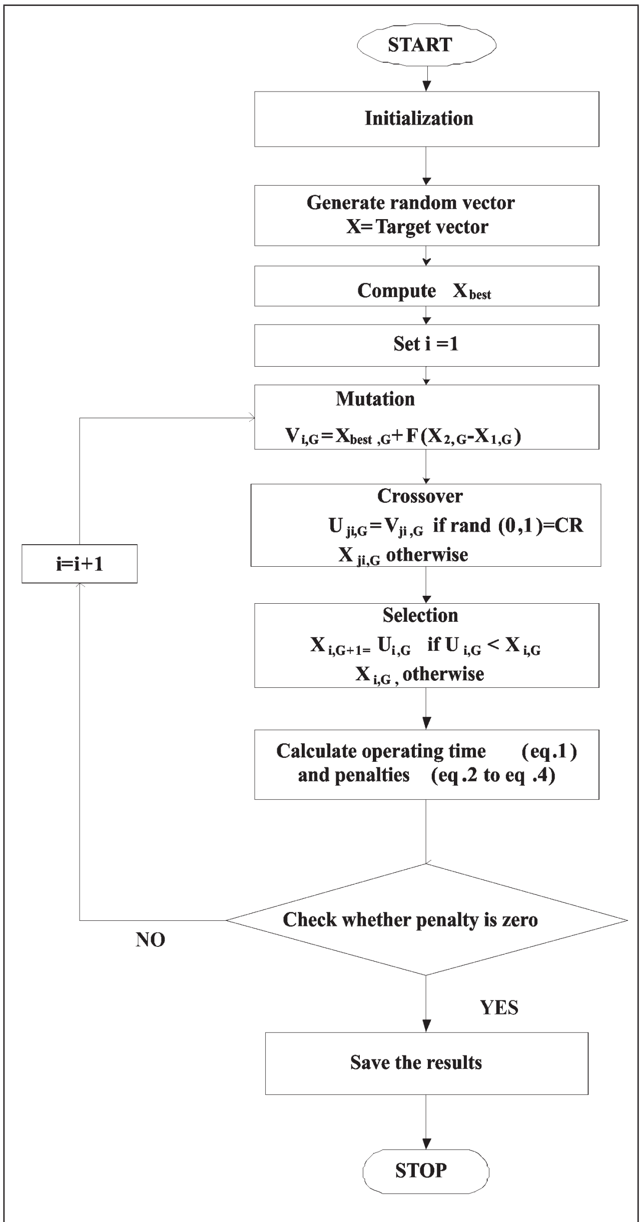

FIG.2 FLOWCHART DEA

Steps involved in DEA

1. Initialize all the parameters used in differential evolution (DE) coding which includes upper and lower bounds, population size, no. of relays used.
2. Generate the vector randomly between the given limits called target vector.
3. Calculate the mutant vector by using below given generated target vector.

Mutant Vectors = Best Target Vector+ F1*(Target $Vector_2$ -Target $Vector_1$).

4. In crossover it will compare with mutant vector and target vector and generate new trail vector.
5. If the penalties generated are zero, then it terminates otherwise step-3 repeats.

3.0 RESULTS AND DISCUSSION

The proposed new voltage current time inverse relay model is implemented in IEEE 9 bus distribution system. The single line diagram of IEEE 9 bus system is as shown in the Figure 3(A). The line data and generators data are taken from [15]. The local circuit DER is connected at bus 1 of 9 bus distribution. The rating of eachPV power station is 25 MVA. The rating of each generator is 100 MVA in Figure 3. The penetration level of DG power in 9 bus distribution system is 50/400=12.5%. There are 36 relays installed at each line end including the DER connected feeders as shown in Fig3 (B). The operating direction of each directional relays are marked in Figure 3.The performance of the proposed relay model is compared with the conventional time inverse relay model as under.

The relay coordination problem is solved as optimization problem and optimised relay settings are obtained with standard time inverse over current relays and proposed voltage-current time inverse model.

The optimised TDS,PSM(in per unit) and voltage pickup(in perunit) and other relay parametersare listed in Table 2 and operating time of each relay corresponding to standard time inverse and proposed relay is computed for line fault and is listed in Table 3

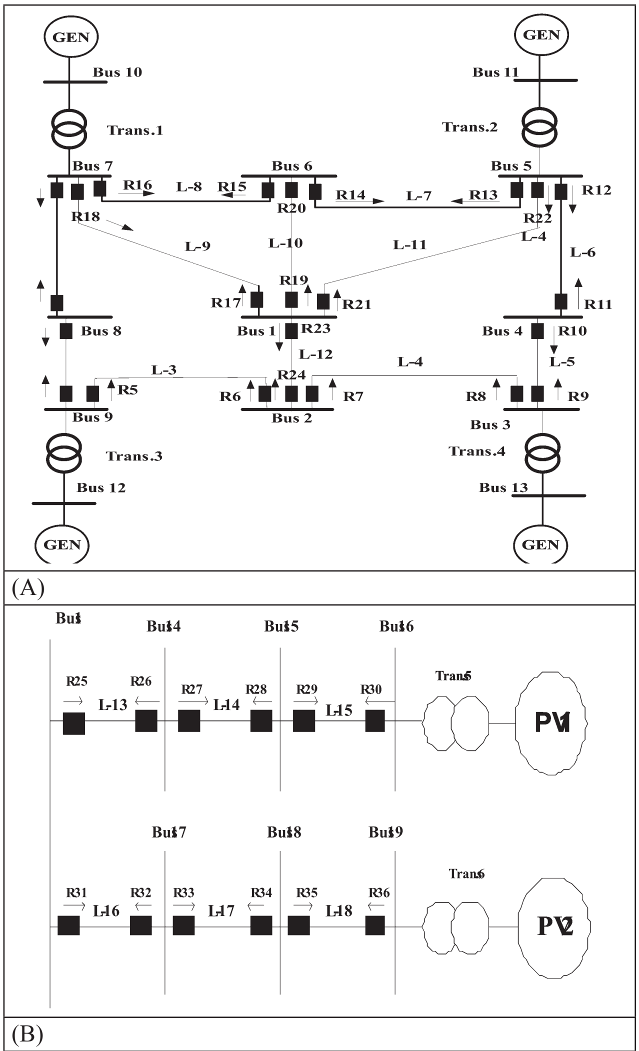

FIG.3. IEEE 9 BUS DISTRIBUTION SYSTEM

TABLE 2

OPTIMISED RELAY SETTING

Relay no	Standard time inverse relay		Proposed relay model				
	TDS	PS	TDS	PS	Vp	A	K
1	0.55	1	0.23	2.5	0.9	3	1
2	0.32	2.5	0.87	2	0.6	4.5	1
3	0.95	0.5	0.16	2	0.8	5	2
4	0.83	0.5	0.99	0.5	0.7	1.5	1
5	0.68	0.5	1	1.5	0.2	1	1
6	0.15	0.5	0.13	2.5	0.8	3.5	3
8	0.67	0.5	0.25	1.5	0.8	1	3
9	0.79	1.5	0.2	1	0.2	4.5	1
10	0.55	2.5	0.82	2.5	0.6	3	1
22	0.52	2.5	1	0.5	0.9	5	2
23	0.58	0.5	0.71	2	0.6	5	1
24	0.55	1.5	0.86	1	0.9	5	2
25	0.53	2	1	2.5	0.3	3	1
26	0.71	0.5	0.95	2.5	0.5	1	3
27	0.41	1	0.58	0.5	0.9	5	2
28	0.57	2.5	0.78	0.5	0.9	5	1
29	0.1	0.5	0.94	1.5	0.5	3.5	3
30	0.96	2.5	0.76	2.5	0.6	1	1
31	0.49	1	0.29	0.5	0.5	5	1
32	0.44	2	0.43	1.5	0.6	1.5	1
33	0.32	0.5	1	1	0.9	1	1
34	0.53	2.5	0.9	1	0.5	1.5	1
35	0.1	0.5	0.1	1.5	0.9	3.5	3
36	0.68	2.5	1	2.5	0.9	1.5	2

The over current relays which are installed in local distribution network of micro-grid shown in Figure 3 (b) have sluggish operating time when they are sensing the fault current from PV based system only. Their operating time is enhanced with the help of new proposed relay model. The operating time of all relays for fault in middle of their corresponding line is mentioned in Table 3 for both the relay models. It is observed that relay which are facing fault current from PV based power station are R26,R28,R30,R32,R34 and R36 during their primary and backup operations. Their operating time is enhanced significantly with the help of proposed relay model. The % change in operating time for relay during their primary and backup operation is listed in Table 3 below for various fault locations. However, in few relays, there is deterioration in operating time due to re- distribution of fault current due to bi-directional flow of the fault current from the remote end PV system. In general, it is observed that there is remarkable improvement in their operating time of primary and backup relays for weak fault currents supplied from the PV based power stations as per Table 4.The performance of the proposed relay model is also analysed in terms of total reduction in value of the fitness function as per Table 5.The improvement in operating time and CTI for primary relay R28 and backup relay R30 for fault at middle of Line-14 is plotted in Figure 4 below corresponding to standard time inverse and proposed relay models.

TABLE 3

RELAY OPERATING TIME (S)

Fault at middle	Standard time inverse relay			Proposed relay model		
	Ri,k=Ti,k	Rj1,k=Tj1	Rj2,k=Tj2	Ri,k=Ti,k	Rj1,k=Tj1	Rj2,k=Tj2
L-1	R1=0.78	R17=1.4	--	R1=0.294	R17=0.596	--
	R2=0.732	R4=1.212	--	R2=0.56	R4=0.942	--
L-2	R3=no trip	--	--	R3=0.06	R1=0.374	--
L-3	R6=0.232	R23=0.93	R8=1.23	R6=0.061	R8=0.362	R23=0.365
L-4	R7=0.276	R23=0.91	R5=1.24	R7=0.06	R23=0.365	R5=0.923
	R8=1.648	R10=2.04	--	R8=0.563	R10=0.909	--
	R14=0.373	R19=0.796	R16=1	R14=0.071	R19=0.48	R16=0.7
L-8	R15=0.356	R19=0.796	R13=1.17	R15=0.165	R19=0.48	R13=0.469
	R16=0.843	R2=1.192	R17=1.72	R16=0.573	R2=0.874	R17=0.888
L-14	R28=1.275	R30=2.147	--	R28=0.734	R30=1.08	
L-15	R29=0.136	R27=0.657	--	R29=0.06	R27=0.369	
L-16	R31=0.609	R20=1.128	R18=1.231	R31=0.061	R20=0.598	R18=0.622
	R32=0.989	R34=1.29	--	R32=0.498	R34=0.801	--
L-17	R34=1.18	R36=1.521	--	R34=0.751	R36=1.644	--

TABLE 4

IMPROVEMENT IN THE OPERATING TIME OF RELAY WITH PROPOSED METHOD

Relay no.	Operating time (s): Standard time inverse relay model		Operating time (s): Proposed relay model		% Change in operating time		Relay no.	Operating time (s): Standard time inverse relay model		Operating time (s): Proposed relay model		% Change in operating time	
	Primary	Backup	Primary	Backup	Primary	Backup		Primary	Backup	Primary	Backup	Primary	Backup
1	0.78	0.94	0.29	0.37	62.3	60.5	19	0.61	0.8	0.32	0.48	47.3	39.7
2	0.73	1.19	0.56	0.87	23.5	26.7	20	0.72	1.12	0.42	0.6	40.6	47
3	1.37	1.18	0.06	0.06	95.6	95	21	0.47	0.83	0.27	0.47	41.1	43.4
4	1.19	1.21	0.92	0.94	22.3	22.3	22	0.94	1.43	0.51	0.68	45.8	52.8
14	0.37	1.26	0.07	0.83	81	0.35	32	0.98	1.34	0.49	0.65	49.6	51.7
15	0.35	1.55	0.16	0.72	53.7	53.5	33	0.4	0.43	1.31	0.11	-228	74.4
16	0.84	1	0.57	0.7	32	30	34	1.18	1.29	0.75	0.8	36.4	37.9
17	0.97	1.4	0.33	0.6	65.4	57.4	36	1.37	1.52	1.48	1.64	137	-8.1

TABLE 5

FITNESS FUNCTION

Method	Fitness function (s)	%Reduction
Standard time inverse relay model	27.735	45.53%
Proposed relay model	15.105	

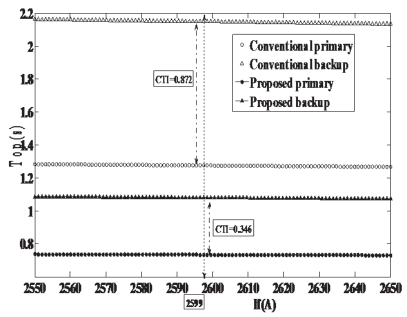

FIG.4 OPERATING TIME CHARACTERISTICS OF R28 AND R30

4.0 CONCLUSION

Operating time of conventional time inverse over current fed with PV based distributed energy resources is extremely poor due to their poor fault feeding capabilities. In this research work, the operating time of over current relays is enhanced by proposing an additional voltage based time inverse function to existing time-inverse over current relay characteristics. The marginal rise in fault current and fall in nodal voltage during faults are inputs for actuating the proposed relay model. For the presented results, it is observed that there is significant reduction in operating time of over current relays particularly when the relay is exposed to fault infeed from photovoltaic based generators.

5.0 FUTURE SCOPE

With the integration of DERs each time fault level changes in the utility network and it requires modification in relay settings. Changing the relay setting is not economically feasible to change the relay settings for each new incoming DER. Therefore there will be need of universal relay setting which can provide the reliable protection for all level DER infeed.

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