CHAPTER-3

HYBRID PICKUP OF THE RELAYS

3.1 Introduction

With the interconnections of DGs, a system is exposed to the fault current of different characteristics with a wide range of levels of fault currents [3]. There are various factors which induces different level of fault currents, where some of the major factors are as follows: changing number and sizes of DGs, grid connected and islanding mode, interconnections of DGs with different short circuit capacities, radial and meshed configuration, symmetrical and unsymmetrical faults with different characteristics, and low impedance and high Impedance faults. To protect a system from different types of fault-conditions, protection schemes based on only one electrical parameter of the feeder-line is not sufficient [103]. For example, schemes based on only overcurrent [18], [60], [90], [99], [103], and [104] may fail to sense the fault in islanding or low fault current situations, and schemes based on only negative sequence current [105], [106] may less sensitive to the symmetrical faults, while voltage-based scheme proposed in [64] is limited to protect only DG-zones from outside faults and fails to protect the network feeders. Thus, it is worthy to mention that a protection scheme for the modern distribution system must be comprehensive so that it can sense the fault and provide the protection from the faults with different levels and characteristics in both grid-connected and islanding mode.

In [60], [93], and [107], an approach is proposed which overcomes the limitations of the previous approaches. Where, various individual protection modules such as overcurrent module, negative sequence module, voltage module, zero sequence module have been embedded in a relay to protect from the different types of fault, where each protection module has its own operating characteristics. In this approach, the overcurrent module uses inverse-time characteristics while other uses definite-time characteristics. This approach provides an effective solution to deal with the different types of faults in grid-connected and islanding operating modes. However, this approach has some major demerits and limitations, discussed as follows, which further put up the need of an improved protection approach.

1. The first demerit is that it raises a need of a separate fault classification module to classify the type of fault (whether it is symmetrical, unsymmetrical, or low/high impedance) so that an appropriate protection module can be selected to clear the occurred fault.
2. The second demerit is that it raises the need of separate mechanism for detecting the current operating mode (for e.g. grid-connected or islanding operating mode) so that an appropriate protection module can be selected to clear the occurred fault.
3. The third demerit is that each time it requires switching of the protection modules at the occurrence of different operating modes or different types of fault cases.
4. The fourth demerit is that the method has been proposed considering the fixed number and sizes. So, it may fail to deal with the fault current level change due to variable number and sizes of DGs.
5. The fifth demerit is as follows. As, this approach is dependent on detection of the current operating mode, so it may get incapacitated to take any action if any unknown operating mode happens due to any sudden change.
6. The sixth demerit is the coordination between relays in the presence of different magnitudes of fault currents. This can be explained as follows: there can be a case where

some relay that will experience enough amount of phase current's magnitude, would select the inverse-time overcurrent protection module, while other relays that experience the lower phase current's magnitude would choose the different protection module with different time grading characteristics. In such type of fault scenario, coordinating the relays based on different actuating quantities and different protection characteristics will be a tedious and complicated task.

7. The seventh demerit is that, other than inverse-time characteristics, most of the protection modules clear fault currents by using definite-time characteristics, which sometimes fails to provide fine selectivity as an inverse-time characteristic can do in the scenario of different fault current levels.

In this chapter, a novel hybrid algorithm has been presented to detect the fault irrespective of the variability of the operating modes and to calculate the pickup-settings of relays with the aim of overcoming the demerits of the existing method and making the protection robust and reliable, and adaptive to the variable operating modes. In this approach, relays are assumed to facilitated with advanced capabilities such as the acquisition of data, self-testing, multifunctioning, data communication, and numeric calculations.

3.2 Proposed Hybrid-algo algorithm for determining the relay's HPMS

3.2.1 Working Procedure

In this hybrid approach of calculating a relay's pick-up setting, a relay not only uses the measurements of phase current's magnitude (I) but also uses the measurements of other electrical parameters including V, I_{neg}, and I_z collected during both pre-fault and fault conditions. It stores their pre-fault values in its memory and modifies them into the reference values (I_{ref}, V_{ref}, I_{neg_ref}, and I_{z_ref}) by multiplying with the corresponding reference multipliers (n_i, n_v, n_{neg}, and n_z). When a fault occurs, the relay compares the measured fault values to its corresponding reference values by calculating Q_1, Q_2, Q_3, and Q_4 ratios using Equation (3.1). Here, Q_1 denotes the ratio of the fault current value to the reference current value, which also indicates the PMS_{old} value for a conventional overcurrent relay. While each of the Q_2, Q_3, and Q_4 ratios denotes the relative difference in the fault value of the corresponding parameter with respect to its reference value. Thus, in this hybrid approach, each Q_i represents the equivalent weightage of the i^{th} parameter that takes part in deciding the operating time of a relay. Based on the corresponding Q values, it generates a_1, a_2, a_3, and a_4 bits using Equation (3.2) corresponding to I, V, I_{neg}, and I_z parameters. Then, it combines all a_i bits as shown in Equation (3.3) to determine the PS for the relay which is responsible for picking up of the relay during a fault condition. This signal possesses the feature of detecting the fault even in the low fault current situation.

$$Q_1 = \left(\frac{I}{I_{ref}}\right), Q_2 = \left(\frac{V_{ref} - V}{V_{ref}}\right), Q_3 = \left(\frac{I^{neg} - I^{neg}_{ref}}{I_{ref}}\right), Q_4 = \left(\frac{I^{z} - I^{z}_{ref}}{I_{ref}}\right) \tag{3.1}$$

$$If,\ Q_i > 0;\ a_i = 1,\ and\ if,\ Q_i \le 0;\ a_i = 0 \tag{3.2}$$

Further, $[a_1 \times (a_2 + a_3 + a_4)] \ge 1;\ PS = 1$

$$[a_1 \times (a_2 + a_3 + a_4)] = 0;\ PS = 0. \tag{3.3}$$

1) Two conditions that enable a relay's pickup signal (PS)

1. The first condition is a_1=1 i.e. presence of the phase-current over a relay irrespective of the level of phase-current with respect to the reference (threshold) current: During a fault, in a system, there are two types of relays, one that doesn't experience the flow of current (for this a_1=0 as per Equation (3.2)), and second that experiences the flow of current i.e. Q_1>0, where for this a_1=1. As a result, as per Equation (3.3), the first type of relays will not send any pickup signal (as PS=0) to the CPC and thus will not take part in the online relay coordination process. Whereas, the second type of relays with a_1=1, irrespective of Q_1>1 or Q_1<1, will get picked up (with PS=1 status) depending upon the second condition (as described below).
2. The second condition is the presence of disturbances in the other measured parameters' values with respect to their reference values: If a relay that experiences a_1=1 meets the disturbances in one or two or all three other parameters (V, I_{neg}, and I_z), then (a_2+a_3+a_4) ≥1, as a result, the relay will experience a faulty situation with [a_1×(a_2+a_3+a_4)] ≥1 condition which will make it picked up with PS=1 status as per Equation (3.3). Then, the relay will send its high PS to the CPC and will take part in the online relay coordination process. On the other side, during a balanced condition, the relays will experience (a_2+a_3+a_4) =0 with a_1=1 and hence will not get picked up, while the default corresponding PS status at the CPC will remain 0.

As a relay senses its PS=1, it quickly calculates its *HPMS* setting by combining the determined Q weightages and ai bits of the parameters by using the given formula in Equation (3.4).

$$HPMS = a_1 \times Q_1 + a_2 \times Q_2 + a_3 \times Q_3 + a_4 \times Q_4 \tag{3.4}$$

3.2.2 Functioning and Significance of the Hybrid Approach

In the presence of the DGs, only the overcurrent parameter-based protection approach fails to protect the system when the fault current goes near or below the value of reference current. This may occur in either of the situations when a relay experiences phase-current: 1. from a low short-circuit capacity (SCC) DG source, 2. with a high/medium fault impedance, 3. in an unsymmetrical fault, and/or 4. in an islanding mode. In all these situations, a relay can experience *PMS* less than 1 at which the conventional overcurrent-based approach fails to detect the fault and to provide the valid constraints and thus valid *TMS* settings. This hybrid approach inherently performs the fault identification and classification and generates a pickup signal along with the corresponding *HPMS* setting for optimizing the *TMS* of the relay. In this approach, there is no requirement of separate fault detector module and any additional information regarding operating modes to deal with the different types of fault situations in variable operating modes. As described in Section 3.2.1, it takes a protective decision which is based on the combine weightages of more than one-line parameters. So, if the weightage of one parameter is low during a fault, then the weightages of other parameters will contribute to detect the fault and yield the valid *PMS* settings. Thus, it provides a platform for the relay coordination, for the fault events with uneven fault current distribution, which is based on a single protection characteristic (i.e. inverse-time) instead of the combination of different characteristics (as in the existing methods) with which coordination of the relays is a tedious task. The comparative functioning of the *HPMS*, with respect to the PSM_{old}, during a high and low fault current situation can be seen in the results shown in Table 3.6 and Table 3.7 in the later Section 3.3.2.

3.2.3 Relays Coordination and Operating times with HPMS settings

The working procedure for determining the *HPMS* is described in the previous Section 3.2.1. While, the step by step determination of *TMS* settings by using the hybrid approach is depicted in the flowchart shown in Figure 3.2 on page no-70. By using the obtained *HPMS*, optimal *TMS* for the relays are determined by minimizing the conventional *OF* (given in (1.2)) subjected to the coordination and operating time constraints as given in (1.3) and (1.4) respectively. With online *HPM*S, constraints are dedicated to the current fault situation in the current operating mode, thus it eliminates the needs of taking the constraints related to the offline maximum near-end and minimum far-end fault currents. As a result, it relaxes

TABLE 3.1

COMPARATIVE PERFORMANCE OF HPMS FOR MESHED GRID-CONNECTED MODE WITH SYNCHRONOUS-DGS (FAULT CASE: LLG FAULT AT Z4, *RF*=4.3)

		With PMS_{old}		With PMS_{old}		With HPMS		
		Offline		*Online*		*Online*		
Relays	*RHs*	*TMS*	T_R	*TMS*	T_R	*RHs*	*TMS*	T_R
R(4u)	Pu	0.0423	0.1454	0.01	0.0343	Pu	0.0148	0.0300
R(3u)	B1u	0.4647	1.5931	0.0975	0.3343	B1u	0.1596	0.3300
R(25u)	B2u	0.0344	11.1184	0.01	3.2322	B2u	0.0179	0.6300
R(2d)	B2u	0.4823	2.9144	0.105	0.6343	B2u	0.1796	0.6300
R(4d)	Pd	0.0100	0.3001	0.01	0.2991	Pd	0.0100	0.1061
R(5d)	B1d	0.1053	3.1483	0.02	0.5991	B1d	0.0381	0.4061
R(29d)	B2d	0.1068	16.8891	0.01	1.5808	B2d	0.0331	0.7061
R(6d)	B2d	0.2464	4.6221	0.0479	0.8991	B2d	0.0863	0.7061
T_R_sum (s)			40.7298		7.6132	*T_R_sum(s)*		3.5445
T_conv (s)			0.0456		0.0294	*T_conv(s)*		0.0260
Tot_constr			16		8	*Tot_constr*		8
Achieved Reduction in *T_R_sum*				81.2% (w.r.t. offline Conventional)		53.5% (w.r.t. online Conv.) 91.3% (w.r.t. offline Conv.)		

significant number of constraints from the optimization process. To show the effectiveness of only the online-based settings, the performance of these settings is compared with the offline based settings which are calculated using the offline near-end and far-end fault currents, while taking the same PMS_{old} for both types of settings. The related results have been shown for both grid-connected and islanding operating mode in the first and second column of the result-tables Table 3.1 and Table 3.2 in later Section (3.3.2). The results show that the online settings significantly reduce Tr_{sum}, Tot_{constr}, and T_{conv} compared to the offline settings. The proposed formulation for determining the operating time of a relay i.e. T_R is shown in Equation (3.5), where A and g are the inverse-time characteristics constants.

$$T_R = \left[TMS \times \left\{ \frac{A}{\left(HPMS\right)^g} \right\} \right] \times PS \tag{3.5}$$

TABLE 3.2
COMPARATIVE PERFORMANCE OF HPMS FOR IN MESHED ISLANDING-MODE WITH IBDGS
(FAULT CASE: A LG FAULT AT Z26, RF=30)

		With PMSold		With PMSold		With HPMS		
		Offline		Online		Online		
	RHs	*TMS*	*T_R (s)*	*TMS*	*T_R (s)*	*RHs*	*TMS*	*T_R (s)*
R(26u)	Pu	0.0122	0.0914	0.0100	0.0749	Pu	0.0100	0.0401
R(27u)	B1	0.0197	1.1869	0.0100	0.6029	B1	0.0173	0.3401
Rdg3_far	B2	0.2231	1.6867	0.1194	0.9029	B2	0.1476	0.6401
R(28u)	B2	0.0102	7.9940	0.0100	7.8553	B2	0.0155	0.6401
R(26d)	Pd	0.0100	0.1781	0.0100	0.1781	Pd	0.0100	0.0836
R(25d)	B1	0.3856	0.9722	0.1896	0.4781	B2	0.1627	0.3836
R(3d)	B2	0.1061	1.8736	0.0440	0.7781	B2	0.0764	0.6836
T_R_sum (s)			13.9829		10.8704	*T_R_sum(s)*		2.8115
T_conv (s)			0.0924		0.0394	*T_conv(s)*		0.0360
Tot_constr			14		7	*Tot_constr*		7
Achieved Reduction in *T_R_sum*				22.3% (w.r.t. offline Conv.)		66 % (w.r.t. online Conv.) 79.8% (w.r.t. offline Conv.)		

The conventional formula of calculating the *Tr* in Equation (1.1) is based on only the overcurrent parameter, where the denominator of the formula contains a ‘minus 1’, using which a relay operates only when the $PMS_{old} > 1$, and doesn’t operate when the $PMS_{old} \leq 1$. So, this operator acts as a relay’s pick-up operator, and in turn, provides valid constraints and operating time only when a relay will experience the fault current greater than the I_{ref}. On the other hand, instead of PMS_{old} shown in Equation (1.2), *Tr* in Equation (3.5) works on both the calculated *HPMS* setting and the calculated *PS which is* a relay’s pick-up operator.

TABLE 3.3

ONLINE CONVENTIONAL PMS AND HYBRID PMS FOR THE RELAYS SHOWN IN TABLE 3.1AND TABLE 3.2

PMS for Table-3.1								
Relays	R(4u)	R(3u)	R(25u)	R(2d)	R(4d)	R(5d)	R(29d)	R(6d)
PSM_{old}	24.2908	24.3367	1.2475	14.2391	3.6749	3.6749	1.5061	5.2641
HPMS	39.3697	38.6943	2.2719	22.8031	7.5382	7.5094	3.7492	9.7812
PMS for Table 3.2								
Relays	R(26u)	R(27u)	Rdg3_far	R(28u)	R(26d)	R(25d)	R(3d)	-
PSM_{old}	11.6750	2.3268	11.5806	1.1018	5.4918	32.7329	5.5284	-
HPMS	19.9273	4.0733	18.4507	1.9385	9.5666	33.9215	8.9463	-

TABLE 3.4

TOTAL SUM OF OPERATING TIMES OF RELAYS IN VARIOUS FAULT CASES IN GRID-CONNECTED MODE

zth	PMS	T_R_sum in Radial (in *s*)						T_R_sum in Mesh (in *s*)			
		SDGs	SDGs	SDGs	IBDGs	IBDGs	IBDGs	SDGs	SDGs	SDGs	IBDGs
		LLLG	LLG	LG	LLLG	LLG	LG	LLLG	LLG	LG	LLLG
		solid	*Rf*=4.3	*Rf*=100	solid	*Rf*=4.3	*Rf*=100	solid	*Rf*=4.3	*Rf*=100	solid
z4	Conv.	3.2964	*(R25u)	6.1162	5.0981	8.2914	4.27874	3.2460	7.6132	23.8981	3.3232
	With HPMS	3.2793	3.8118	4.6964	3.4972	3.9956	4.2579	3.2400	3.5445	5.5759	3.2792
z29	Conv.	4.8567	5.7166	*(Rdg5_far, Rdg1_far)	5.2425	*(R6d, Rdg5_far, R29d, R30d, Rdg1_far)	*(Rdg5_far, Rdg1_far)	4.8100	8.6529	*(R6d, R7d, Rdg5_far, Rdg1_far)	5.1776
	With HPMS	4.8393	5.0244	8.5858	5.0966	5.7316	6.6996	4.8000	4.9014	9.9919	4.8065

*These relays have failed to detect the fault by using *PMSold*’

3.3 COMPARATIVE PERFORMANCE OF THE HPMS RELAY SETTING AND RESULT DISCUSSION

3.3.1 Simulation Setup

The performance of the HPMS has been demonstrated on the same IEEE 38-bus test distribution system in Figure 2.1. Where this test system can work as a radial network when all tie lines are open, and as a meshed network with 5 loops when all tie lines are connected. The Matlab simulation setup for grid-connected and islanding modes are described as follows. For grid-connected mode, six DGs, each of 1.5 MVA capacity, are connected at nodes 6, 26, 24, 9, 29, 21 as shown in Figure 2.1. Each DG is connected with a local load of the same capacity as DG with unity power factor to maintain the load-supply balance of the test system. While for the islanding mode's operation, a microgrid has been formed by disconnecting the R^{2u}, R^{6u} and R^{33d} relays in the network in Figure 2.1. This islanding network contains only two DGs (DG1 and DG3). Where to balance the load-demand and supply, the capacity of each DG is taken as 1 MVA. The type of DG can be synchronous-based (SDG) or inverter-based (IBDG). The SCC of a synchronous DG and an IBDG are taken as 5 times and 2 times the DG's rated capacity respectively. The relay coordination problem has been formulated as a linear problem, where only *TMS* relay setting is optimized while *PMS* is taken as a constant. In this study, the rms values of the electrical parameters have been considered, and while computing the *HPMS*, n_i=1.2, n_v = n_{neg}= n_z =1 have been taken. In the coordination study, T_P*_min*=0.03s, *TB1_min*=0.33s, *TB2_min*=0.63s are the minimum limits specified for the operating times of the relays with P, B1, and B2 hierarchies respectively, and *TMS_min*=0.01, and *CTI_min*=0.3s are the minimum limits for *TMS,* and coordination time interval respectively. To compare the performance on the same scale, same characteristics constants for relays, i.e. *A*=80 and *g*=1 have been selected.

3.3.2 Comparative Performance and Advantages of the HPMS

Various fault-cases have been investigated and compared to show the effectiveness of the proposed HPMS with respect to the conventional method of calculating the PMS_{old} adopted by the existing protection schemes [14], [18], [60], [90], [92], [93], [99] [103]-[105], [107]. Where, in the conventional method, a *PMS* (i.e. PMS_{old}=[I/Iref]) is calculated by using only the overcurrent measurements, while in the proposed method, it has been calculated using the measurements of multiple electrical parameters (as described in Section 3.2.1). To show the influence of the HPMS only, the same formulation of the *OF* (in Eq.(1.2)) and conventional unidirectional relays hierarchies have been used in both methods. While the operating time has been calculated by using Equation (3.5) and (1.1) respectively for the proposed and conventional method. Different fault cases have been conducted for different types of faults

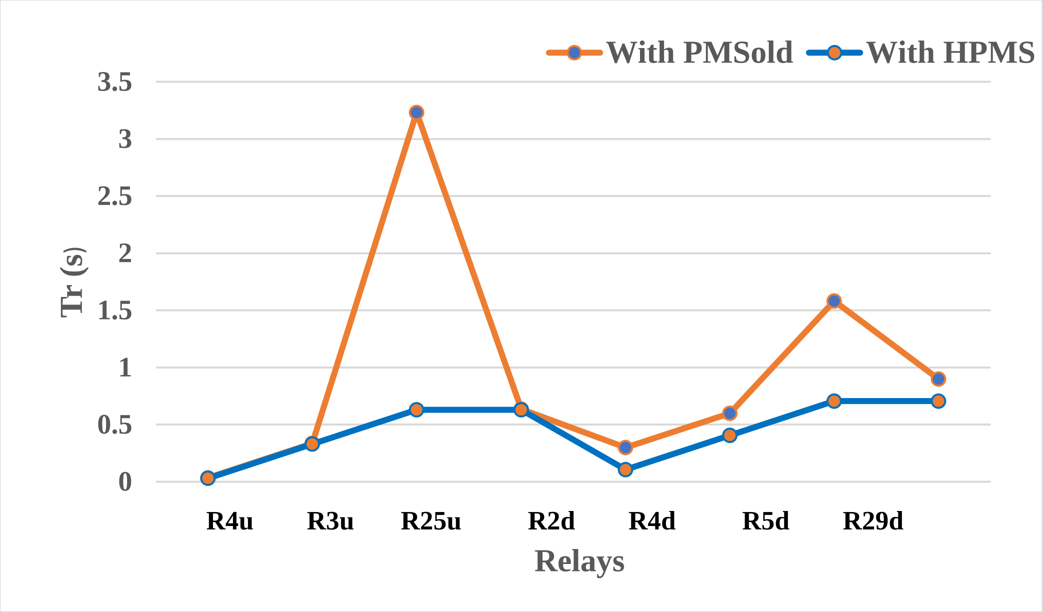

Figure 3.1 Comparison of relays operating times (Tr) obtained using PMSold and HPMS for the Fault case (LLG fault with Rf=4.3 at z4) in Meshed Grid-connected operating mode with syn_DGs

with variable *Rf* in radial or meshed for both grid-connected and islanding operating modes. The case studies have been performed for both types of DGs, synchronous-types and IBDG-types, which possess a significant difference in their SCC capacities. The Tables 3.1 and Table 3.2 show the RHs, *TMS*, and *Tr*, and Table 3.3 shows the obtained online PMS_{old} and *HPMS* settings for both tables Table 3.1 and Table 3.2. Table 3.4 and Table 3.5 show the total sum of operating times of relays (*Tr_sum*) obtained for different fault cases. The comparative performance and advantages of the proposed hybrid approach have been described below:

TABLE 3.5

TOTAL SUM OF OPERATING TIMES OF RELAYS IN VARIOUS FAULT CASES IN ISLANDING MODE WITH IBDGS INTERCONNECTIONS (IN SEC)

PMS		Fault Location - Z29					Fault Location - Z26			
		LLG, *Rf* =15		LLG, *Rf*=30			LG, *Rf*=10		LG, *Rf*=20	
		Mesh	Radial	Mesh	Radial		Mesh	Radial	Mesh	Radial
Conv.		6.9672	3.5822	* R29u	5.3272		4.7375	3.8953	8.0706	6.3572
HPMS		3.3894	2.5157	3.8568	2.8267		2.6836	2.0146	2.7364	2.0688

*Relays failed to detect the fault by using PMS_{old}’

a. Dedicated Protection

The proposed hybrid approach relaxes numerous constraints while takes the online fault values of the current operating mode to determine the online-based *HPMS* which makes it a *PMS* dedicated to the current fault situation. The dedicated settings are relatively more optimal and provide effective performance as explains in the next section.

b. Fast Fault Clearance

It can be observed from the second and third column of the result-tables Table 3.1 and Table 3.2 that the replacement of the PMS_{old} with the *HPMS* effectively reduces the individual relays operating time and gives faster total relays operating time in both grid-connected and islanding operating modes. For e.g., as shown in the Table 3.1, by using the proposed hybrid approach, 91.3% reduction can be achieved compared to the offline Conv. Settings while maintaining the *CTI* margin. Figure 3.1 also gives an idea of reduction in the relays operating times obtained using *HPMS* compared to PMS_{old}. Now, to further validates the overall fast fault-clearance performance of the hybrid approach, the results are also shown in Table 3.4 and Table 3.5 for different fault situations.

TABLE 3.6

Q WEIGHTAGES OF THE PARAMETERS EXPERIENCED BY RELAY ***R25U*** WHEN THE FAULTED ZONE IS Z4 IN THE OPERATING MODE (GRID CONNECTED, RADIAL, SYN-DGS)

	I	V	I_{neg}	I_z
Pre-fault values	46.5195	10322	0.0239e-4	0.0354e-4
Ref. values	55.8234	10322	0.0239e-4	0.0354e-4
LLLG, R_f = 0.001Ω				
Fault values	263.4	3526.5	0.0025	0.9772e-3
* Q_i weightages	4.7177	0.6584	0.0174e-3	0.0449e-3
PMS	$\boldsymbol{PMS_{old}}$ = 4.7177		***HPMS*** = 5.3761	
LLG, R_f = 4.3Ω				
Fault values	30.3	9041	22.5530	22.4219
*Q_i weightages	0.5420	0.1242	0.4040	0.4017
PMS	$\boldsymbol{PMS_{old}}$ = 0.5427		***HPMS*** = 1.4718	

*a_i bit corresponding to all Q_i will be 1 because here all $Q_i > 0$

c. *Detect fault irrespective of the level of fault current:*

The results in Table 3.4 and Table 3.5 show that, by using the conventional approach, some relays failed to detect the fault in some of the low fault current situations. While the hybrid approach not only successfully detects the fault but also provides the optimal and reduced relays operating times in all the low fault current situations. To explain further, the functioning of the hybrid approach in a high (solid LLLG fault) and a low (LLG fault with the given R_f) fault current situations have been explained by using the two failed relays, R25u and R29u,

TABLE 3.7

Q WEIGHTAGES OF THE PARAMETERS EXPERIENCED BY RELAY ***R29U*** WHEN THE FAULTED ZONE IS Z29 IN THE OPERATING MODE (ISLAND, MESH, IBDGS)

	I	V	I_{neg}	I_z
Pre-fault values	24.4366	10321	0.0018	0.0018
Ref. values	29.32392	10321	0.0018	0.0018
LLLG, R_f = 0.001Ω				
Fault values	91.0722	0.3698	0.0023	0.2199e-3
* Q_i weightages	3.1057	1.0000	0.0176e-3	-0.0001
PMS	PMS_{old} = 3.1057		***HPMS*** = 4.1057	
LLG, R_f = 30Ω				
Fault values	26.9532	5145	42.6852	10.4868
Q_i weightages	0.9192	0.5017	0.6009	0.3576
PMS	PMS_{old} = 0.9192		***HPMS*** = 2.3793	

*a_i bit corresponding to all Q_i will be 1 except Q_4 because $Q_4 < 0$

that are mentioned in the first row of Table 3.4 and Table 3.5 respectively. Table 3.6 and Table 3.7 show that the relay's conventional *PMS* (PMS_{old}) goes lower than 1 in the presence of low fault current situation, which results in failure in the detection of the fault and failure in providing the valid constraints for the optimization. On the other side, the *HPMS* utilizes the weightages of the other parameters and consequently detects the fault successfully and determines the valid constraints even when the weightage corresponding to the phase current parameter (Q_1) is low during the fault. In contrast, in the high fault current situation (when Q_1 is high or sufficient), it can be seen in the results that the proportions of the Q_2, Q_3, and Q_4 in the *HPMS* are low compared to the Q_1 while Q_1 dominates in deciding the relay's operating time.

d. Comprehensive, reliable, and robust protection

The results show that a multi-parameters-based hybrid *PMS* approach is able to protect the feeders comprehensively from various kinds and levels of faults with faster fault clearing time and maintaining CTI. Unlike the existing schemes [60], [93], and [107] there is no need to implement different protection strategies to make the relay picked up in various kinds of fault cases such as related to high or low fault impedance, grid-connected or islanding, radial or meshed configuration, and synchronous and asynchronous DGs. Thus, the application of this hybrid approach makes the protection independent of the changes in operating modes, types of fault, and the magnitude of fault currents while provides reliable and robust protection.

3.4 CONCLUSION

This chapter investigates the performance of conventional OCR in different fault situations with DGs. The results show that in low fault current situations, the conventional protection based on only overcurrent parameter sometimes yields delayed protection while in some cases, fails to pick up the relays during a fault. This chapter proposes a novel hybrid approach of calculating the inverse-time based hybrid pickup multiplier setting (HPMS) which takes other parameters of the system, besides phase current, into account. The proposed HPMS works independently of the knowledge of grid connected mode or islanding mode, network configuration, types and size of DG, types of a fault, and levels of fault, and concludingly, able to detect a faulty situation irrespective of a fault condition. Hence, no need to switch protection modules upon changes in the faulty situations. The existing multi-modules approach that employs different protection modules, may fail to coordinate the relays during a fault with a wide range of levels, because of employing the different characteristics (such as inverse-time and definite-time) for relays. On the other hand, the proposed approach provides the same inverse-time characteristics platform for all relays to clear such fault. This advantageous feature makes the coordination easy in fault situations with different fault current level.

Moreover, compared to the definite-time characteristics, it provides fine selectivity, minimal summation of operating times of relays. The results show that besides these advantages, it provides faster relays operating times in both grid-connected and islanding modes.

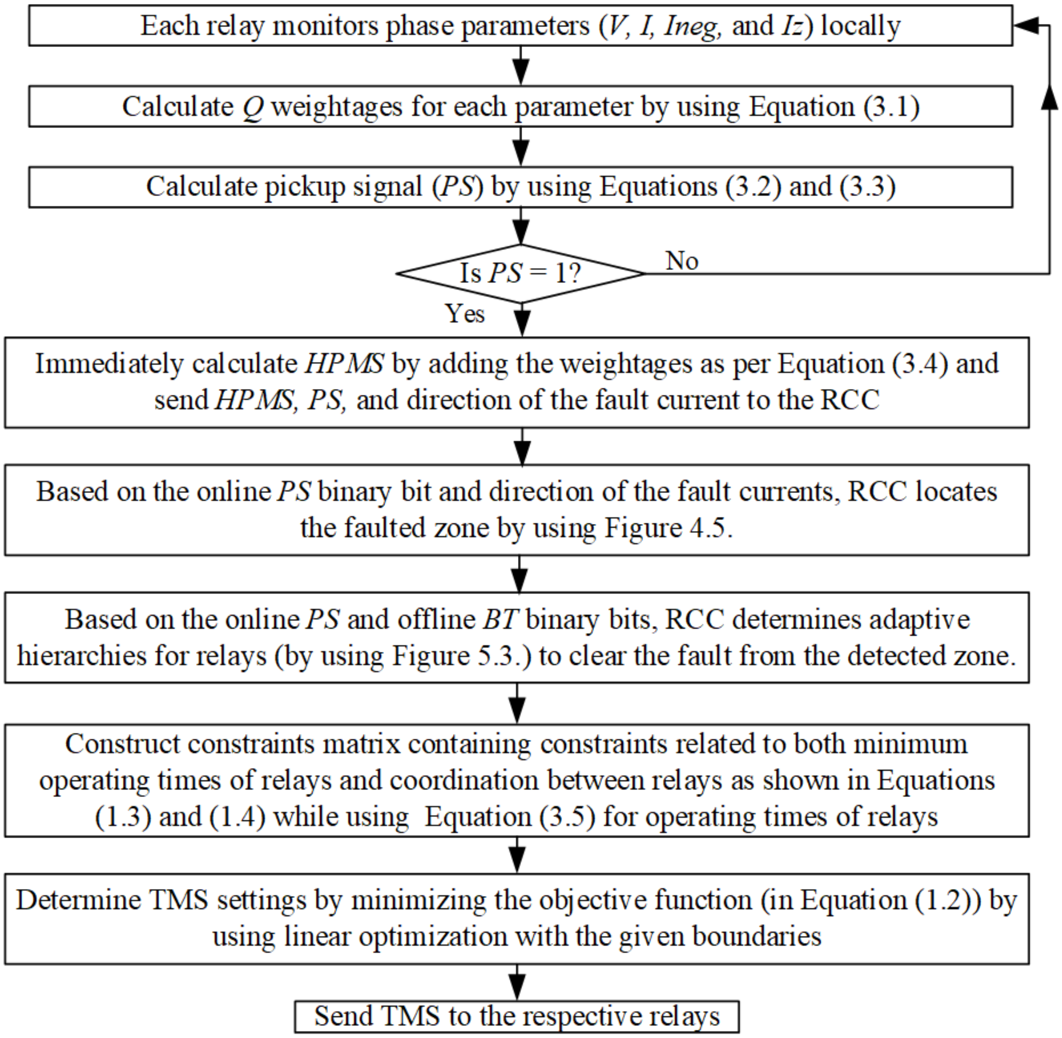

Figure 3.2 Flowchart for determining the settings of relays using the proposed Hybrid_algo