CHAPTER 6

COMPREHENSIVE ADAPTIVE PROTECTION SCHEMES (CAPS) FOR VARIABLE DISTRIBUTION SYSTEM WITH DGS

6.1 Introduction

This chapter proposes comprehensive adaptive protection schemes (CAPS) with the objective of developing a fast, reliable, and robust protection scheme for the varying operational status of the DGs-distribution system in the environment of information loss due to FRC event. In this chapter, two different protection schemes, namely CAPS-1 and CAPS-2, have been designed by accumulating the different algorithms proposed for different protection stages, as described in the previous chapters. The objective of designing the CAPS-1 is to develop a protection scheme for the variable distribution system where the number of DGs can vary during the normal conditions. On the other hand, the objective of designing the CAPS-2 is to develop a protection scheme for the variable distribution system where the number of DGs can vary during both the normal and faulty conditions. Where, changes in the number of DGs during a faulty condition can happen due to the presence of DGs possessed with low fault ride through capabilities. The proposed algorithms (Hybrid_algo, DFZD_algo, and RHs_algo) have been used in designing both protection schemes, CAPS-1 and CAPS-2. While, in the CAPS-2, to deal with the variable number of DGs during a fault condition, a new relay coordination method, named Smart Constraints Reduction based Relay Coordination (SCRRC), developed by using the proposed CRRC method (in Chapter-2) and some information gathered from the system, has been proposed in this chapter.

6.2 Protection Scheme-1 (Caps-1) Considering Variable Operating Modes During Normal Conditions

6.2.1 Working Procedure of CAPS-1

In this section, the working procedure of CAPS-1 has been explained. Different stages of the CAPS-1 is designed by using a sample feeder network of z^{th} zone shown in Figure 6.1 and block diagram. Where, in the shown sample network, R1 and R4 are the end-relays (R^{er}) of the z^{th} zone, while other relays are the adjacent relays. The workflow and block diagram of the protection scheme is depicted in Figure 6.3 and Figure 6.2 respectively. As the workflow shows, this protection scheme is the amalgamation of the proposed algorithms/methods (Hybrid_algo,

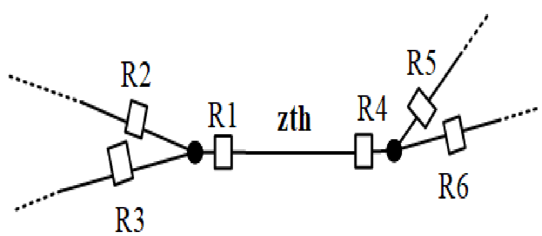

Figure 6.1 A sample feeder network of z^{th} zone

Table 6.2
CAPS-1 at Stage 1

Parameters	R1	R2	R3	R4	R5	R6
BT	1	1	1	1	0	0
FDb	(+1)	(-1)	(-1)	(-1)	(+1)	(+1)
RDb	0	0	0	0	0	0
PS	0	0	0	0	0	0
RHs	NH	NH	NH	NH	NH	NH
HPMS	---	---	---	---	---	---
TMS	---	---	---	---	---	---

Table 6.1
Different Online and Offline Parameters

Signals and bits	Full forms	**Offline and Online Parameters in algorithms**
BT	Backup Tripping bit	(offline stored in RCU)
FDb	Fixed Reference bit	(offline stored in RCU and relay)
RDb	Relay Direction bit	(online calculated in relay)
PS	Pickup Signal	(online calculated in relay)
RHs	Relays Hierarchies	(online calculated in RCU)
HPMS	Hybrid Pickup Multiplier Setting	(online calculated in relay)
TMS	Time Multiplier Setting	(online calculated in RCU)

DFZD_algo, and RHs_algo), where these algorithms involve different offline and online parameters. These parameters are summarized in Table 6.1. The change in the status of different parameters at different stages of the protection has been described as below.

a) Stage-1: Initialization (During Normal Conditions)

In the normal condition, until the *PS* signal calculated by the relay is low, the relay will not send any *RDb* and *HPMS* to the RCU and the 'Sw' switch (in Figure 6.2) will be closed. Resulting of which, the default status of the *PS* and *RDb* at a RCU will be low, as shown in Table 6.2. In the initializing stage, at a RCU, the default status of the RHs will be NH i.e. 'No Hierarchy', while BT is decided based on the pre-decided pattern of backup tripping and, *FDb* is calculated using the CC method given in Section (4.2.1). All the relays will be updated with the *FDb* and *BT* bits which are generally fixed for a system with fixed configuration. At the same time, all the relays will get prepared with their reference values calculated by using the measured local values of (V, I, Ineg, Iz) parameters as described in Section 3.2.1. The initializing status of all parameters at RCU are shown in Table 6.2.

b) Stage 2: Online Calculation in relays and Transfer data from relays to RCU (As fault occurs)

The main action implemented in this stage is shown in Figure 6.4. In this stage, as a fault occurs at the z^{th} zone, the relay will experience high *PS* signal as explained in Section 3.2.1. As a result, it will calculate *RDb* and *HPMS* signals by using the Section (4.2.1) and (3.2.1) respectively, and then will send the values of both signals to the RCU by closing the switch 'Sw' in Figure 6.2. The status of all parameters at RCU upto this stage is shown in Table 6.3.

Table 6.3
CAPS-1 at Stage 2

Parameters	R1	R2	R3	R4	R5	R6
BT	1	1	1	1	0	0
FDb	(+1)	(-1)	(-1)	(-1)	(+1)	(+1)
RDb	+1	+1	+1	-1	-1	-1
PS	1	1	1	1	1	1
RHs	NH	NH	NH	NH	NH	NH
HPMS	HPMS1	HPMS2	HPMS3	HPMS4	HPMS5	HPMS6
TMS	---	---	---	---	---	---

Table 6.4
CAPS-1 at Stage 3

Parameters	R1	R2	R3	R4	R5	R6
BT	1	1	1	1	0	0
FDb	(+1)	(-1)	(-1)	(-1)	(+1)	(+1)
RDb	+1	+1	+1	-1	-1	-1
PS	1	1	1	1	1	1
RHs	P	B1	B1	P	B1	B1
HPMS	HPMS1	HPMS2	HPMS3	HPMS4	HPMS5	HPMS6
TMS	TMS1	TMS2	TMS3	TMS4	TMS5	TMS6

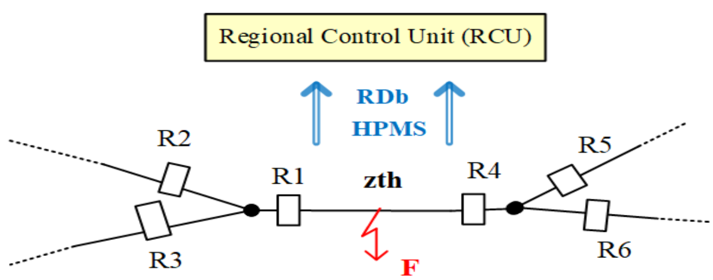

Figure 6.4 Transfer data from relays to RCU in Stage-2

c) Stage-3: Online Processing at RCU

After receiving the available online data from the relays in stage-2, in the current stage, the RCU runs the proposed algorithms in a sequential workflow as described in Figure 6.3, and finally determines the adaptive relays settings. As the stage 2 completes, the RCU first starts to find the faulted zone by using the DFZD-algo (proposed in Chapter 4), then it determines the adaptive hierarchies for the detected faulted zone by using the RHs-algo (proposed in Chapter 5). Then, based on the determined RHs and gathered *HPMS* settings, RCU immediately calculates TMS by using Section 3.2.3. The relay coordination method described in the Section 3.2.3 coordinate the relays dedicatedly for the current operating mode, and thus provides dedicated relays settings. The final status of the parameters in this stage can be seen in Table 6.4.

d) Stage-4: Tripping of the relays

This stage is explained by using the Block diagram of the protection scheme-1 as explained in Figure 6.2. As shown in Figure 6.2, as a relay receives a *TMS* setting, it calculates its operating time by using (e3) (in Section 3.2.3) and starts running an inbuilt timer for the period of T_R. Now, as the timer completes this time period, it stops running with high relay-timer status i.e. *RT*=1, as a result, the relay sends a trip signal to the associated circuit breaker (CB). If CB trips successfully, the relay experiences negative-triggered *PS* (i.e. from 1 to 0) and resets itself by resetting *PS*, *HPMS*, *TMS*, T_R and *RT*. Before resetting, the relay sends its current status including *PS* and its connecting status i.e. *C* (where *C*=*PS*) to update the CPC. Here, the status of *C* can be '0' or '1' which respectively denotes that the relay's CB has been disconnected or still connected to the feeder. On the other side, if, even after completing the timer-loop, relay experiences *PS*=1, then this denotes that the relay's CB has been failed to trip. In this situation, the relay sends its *PS*=1 and *C*=1 (*C*=*PS*) status to the CPC and waits for the successful operation of its backup relays with succeeding hierarchies, until it experiences *PS*=0. Then, as the relay experiences the negative triggering of *PS*, it resets itself after sending the *PS* and *C* to the CPC. Now, during the timer-loop, if a backup relay experiences *PS*=0 due to the clearance of fault by the relay with preceding hierarchy, then it will not send any trip signal to the CB. But it will send its *PS*=0 (-ve triggered) and C=1 ($C = \overline{PS}$) status to update the relay's status to the CPC and then will reset itself. By using the updated 'C' signals, the RCU would get updated itself with the current feeder configuration of the system.

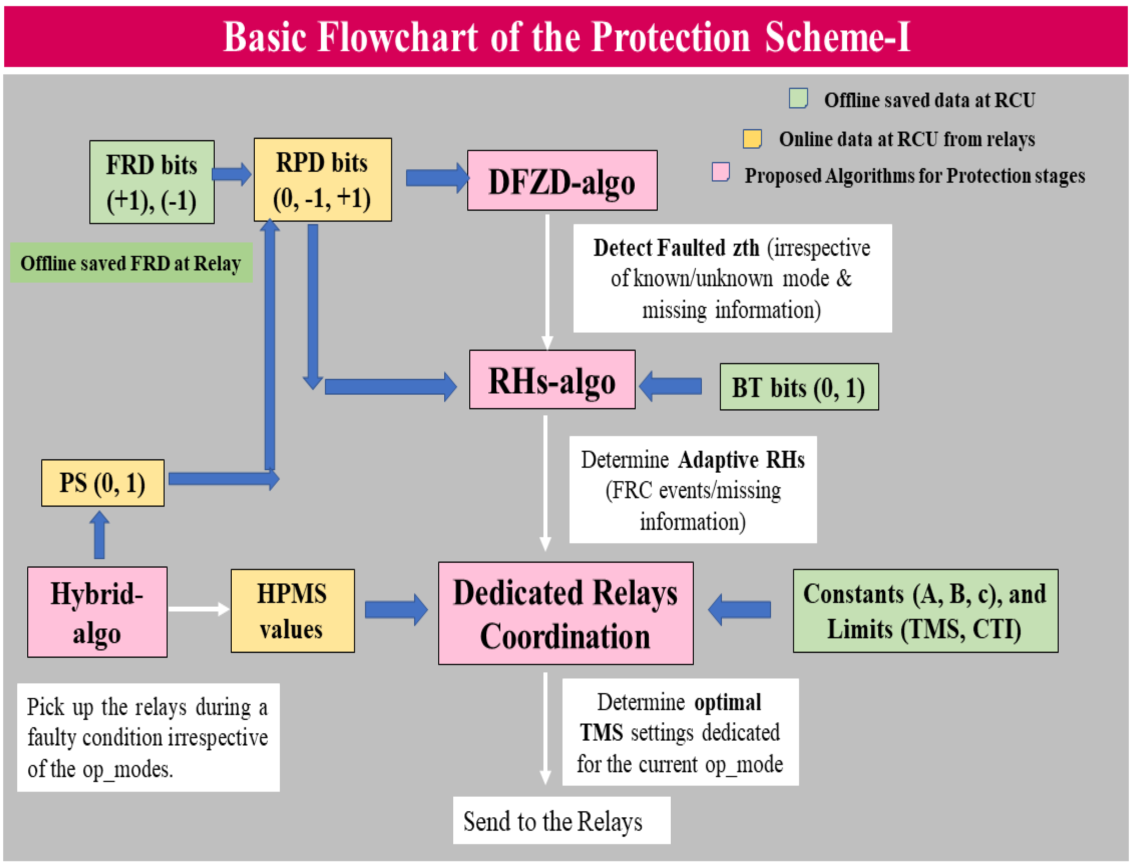

Figure 6.3 Workflow of the CAPS-1

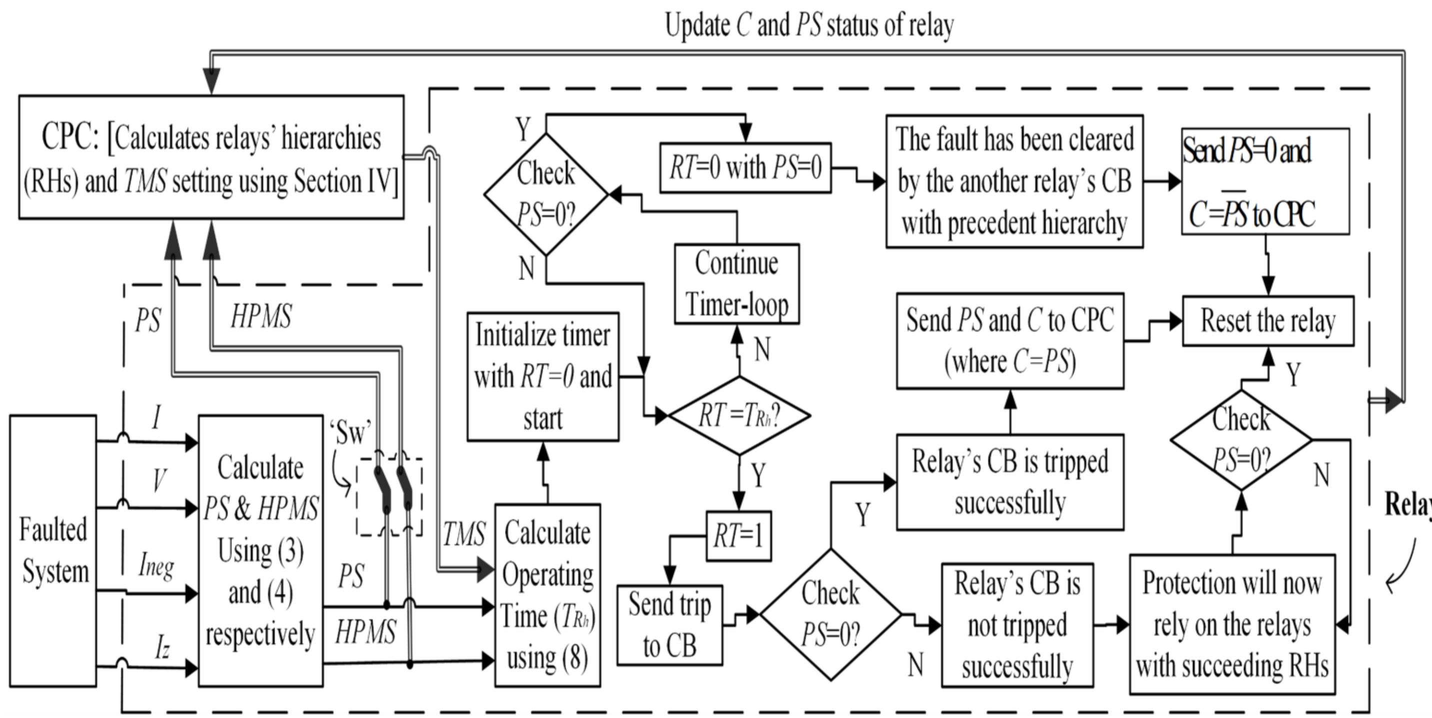

Figure 6.2 Block Diagram of the CAPS

TABLE 6.5
Comparative Performance of CAPS-1 in Meshed Grid-connected Mode with Synchronous-DGs
(Fault case: a LLG fault at z4, Rf=4.3)

	Conventional (Conv.) Scheme			Proposed CAPS-1					
	For both Non-FCR & FRC			Non-FRC			**FRC[1]		
Relays	*RHs*	*TMS*	T_R^h	*RHs*	*TMS*	T_R^h	*RHs*	*TMS*	T_R^h
R(4u)	Pu	0.01	0.0343	Pu	0.0148	0.03	Pu	0.0148	0.03
R(3d)	*	-	-	B1u	0.1625	0.33	B1u	0.1625	0.33
R(3u)	B1u	0.0975	0.3343	B2u	0.3047	0.63	B2u	0.3047	0.63
R(25d)	*	-	-	*	-	-	*	-	-
R(25u)	B2u	0.01	3.2322	*	-	-	*	-	-
R(2u)	*	-	-	*	-	-	*	-	-
R(2d)	B2u	0.105	0.6343	*	-	-	*	-	-
R(4d)	Pd	0.01	0.2991	Pd	0.01	0.1061	*	-	-
R(5u)	*	-	-	B1u	0.0383	0.4061	Pd	0.01	0.1061
R(5d)	B1d	0.02	0.5991	B2u	0.0663	0.7061	B1d	0.0381	0.4061
R(29u)	*	-	-	*	-	-	*	-	-
R(29d)	B2d	0.01	1.5808	*	-	-	*	-	-
R(6u)	*	-	-	*	-	-	*	-	-
R(6d)	B2d	0.0479	0.8991	*	-	-	*	-	-
T_r_sum (s)		7.6132		2.2084			1.5023		
T_conv (s)		0.0294		0.0228			0.0209		
Tot_constr		8		6			5		
Achieved Reduction in *Tr_sum*				70.9% (w.r.t. online Conventional)			31.9% (w.r.t. Proposed (Non-FRC))		

** FRC[1] with R(4d). '*' symbol denotes the 'NH' i.e. 'No-Hierarchy' of the relay

TABLE 6.6
COMPARATIVE PERFORMANCE OF CAPS-1 IN MESHED ISLANDING-MODE WITH IBDGS
(FAULT CASE: A LG FAULT AT Z26, RF=30)

	Conventional (Conv.) Scheme			Proposed CAPS-1					
	For both Non-FCR & FRC			Non-FRC			**FRC[1]		
Relays	*RHs*	*TMS*	*Tr*	*RHs*	*TMS*	*Tr*	*RHs*	*TMS*	*Tr*
R(26u)	Pu	0.0100	0.0749	Pu	0.0100	0.0401	Pu	0.0100	0.0401
R(27d)	*	-	-	B1	0.0177	0.3401	B1	0.0177	0.3401
R(27u)	B1	0.0100	0.6029	B2	0.0326	0.6401	B2	0.0326	0.6401
Rdg3_nr	*	-	-	*	-	-	*	-	-
Rdg3_far	B2	0.1194	0.9029	*	-	-	*	-	-
R(28d)	*	-	-	*	-	-	*	-	-
R(28u)	B2	0.0100	7.8553	*	-	-	*	-	-
R(26d)	Pd	0.0100	0.1781	Pd	0.0100	0.0836	*	-	-
R(25u)	*	-	-	B1	0.2568	0.3836	Pd	0.0201	0.0300
R(25d)	B1	0.1896	0.4781	B2	0.2899	0.6836	B1	0.1399	0.3300
R(3u)	*	-	-	*	-	-	*	-	-
R(3d)	B2	0.0440	0.7781	*	-	-	*	-	-
Tr_sum (s)		10.8704		2.1713			1.3804		
T_conv (s)		0.0394		0.0220			0.0212		
Tot_constr		7		6			5		
Achieved Reduction in *Tr_sum*				73 % (w.r.t. online Conv.)			35.4% (w.r.t. CAPS-1 (Non-FRC))		

** FRC[1] with R(26d) '*' symbol denotes the 'NH' i.e. 'No-Hierarchy' of the relay

6.2.2 COMPARATIVE RESULTS AND ADVANTAGES OF CAPS-1

- **OBTAINED RESULTS**

The effectiveness of the CAPS-1 is shown by comparing it by the conventional protection scheme [18], [20], [90], [103] for both Grid-connected mode and islanding mode. Both test systems and simulation setup are same as described in Section (3.3.1). In the conventional scheme, a *PMS* (i.e. PMS_{old}=[*I*/I*ref*]) is calculated by using only the overcurrent measurements and the RHs are determined by using the unidirectional backup tripping approach. While the minimization *OF* and calculation of the operating time of the relays can be seen in Section (3.3.1). On the other hand, in the proposed scheme, the minimization *OF* and calculation of *Tr* can be seen in Section (3.2.3). To compare the schemes on the same scale, the settings have been obtained for the detected individual faulted zone.

Various results have been obtained, where Table 6.5 and Table 6.6 respectively show the results obtained for Grid-connected mode with synchronous DGs and an islanding mode with IBDGs. These results show that the CAPS-1 not only maintains the coordination margin between the relays but also provides reduced *Tr_sum* in both modes. Besides this, it also relaxes the number of constraints i.e. *Tot_constr* and optimizes the settings in a shorter time by reducing *T_conv*. More results have been shown in Table 6.7 and Table 6.8 which further testify the same above-discussed advantages of the CAPS-1. The results of Table 6.7 and Table 6.8 also verify that with the conventional scheme, some relays fail to detect the fault in some low fault current situations while the CAPS-1 successfully detects and clears the fault. The next sub-section discusses the advantages of the CAPS-1 in detail.

TABLE 6.7

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

Zone	FRC Event	Protection Scheme	T_r_*sum* in Radial						*Tr_sum* in Mesh			
			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	In Both Non-FRC & FRC	Conv.	3.2964	*(R25u)	6.1162	5.0981	8.2914	4.27874	3.2460	7.6132	23.8981	3.3232
	Non-FRC	CAPS-1	2.0095	2.4089	3.0723	2.1729	2.5467	2.7434	1.9800	2.2084	3.7319	2.0094
	FRC[1] (R4d)	CAPS-1	1.3697	1.6359	2.2051	1.4786	1.7278	1.9542	1.3500	1.5023	2.6955	1.3696
	FRC[2] (R4d, R4u)	CAPS-1	0.7397	1.0059	1.4418	0.8486	1.0978	1.2248	0.7200	0.8723	1.8766	0.7396
Z29	In Both Non-FRC & FRC	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
	Non-FRC	CAPS-1	3.5695	3.7083	5.0638	3.7624	5.3674	4.6269	3.5400	3.6160	8.5567	3.5449
	FRC[1] (R29u)	CAPS-1	1.7491	2.0991	3.5728	2.0540	3.5731	2.9210	1.7100	1.8583	5.9508	1.7149
	FRC[2], (R29u, R6d)	CAPS-1	1.0843	1.3287	2.4482	1.3332	2.3309	1.9648	1.0500	1.1622	3.8969	1.0549

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

TABLE 6.8

Total Sum of Operating Times of Relays (in s) In various Fault cases in Islanding Mode with IBDGs Interconnections

Scheme	Non-FRC/FRC	Fault Location - Z29					Non-FRC/FRC	Fault Location - Z26			
		LLG, *Rf* =15		LLG, *Rf*=30				LG, *Rf*=10		LG, *Rf*=20	
		Mesh	Radial	Mesh	Radial			Mesh	Radial	Mesh	Radial
Conv.	Non- FRC	6.9672	3.5822	* R29u	5.3272		Non-RCF	4.7375	3.8953	8.0706	6.3572
CAPS-1	Non- FRC	2.7098	2.5098	3.1448	2.6991		Non-RCF	2.0536	2.0132	2.1035	2.0623
	FRC [1], R29u	1.8181	1.7485	2.1059	1.9764		FRC [1], R25d	1.6716	1.3777	1.4352	1.4228
	FRC [2] (R29u, R30u)	1.1385	1.0370	1.3939	1.2241		FRC [2], (R25d, R27d)	0.9773	0.7431	0.8024	0.7792

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

- **ADVANTAGES OF THE CAPS-1**

1. ***Provides Dedicated protection and avoids protection latency***

Unlike the conventional scheme, instead of using the pre-determined values for RHs, pickup settings, and TMS, this protection scheme uses the post-fault online signals for protective decision-making. Due to which, the protection provided by this scheme is dedicated to the current system's condition. Where the system current's condition can be related to the known or unknown operating mode and FRC event. This is explained by using the Tables 6.5 to Table 6.8. The result-tables show that in the FRC event (unknown), the conventional method clears the fault in the same amount of time as it takes for the Non-FRC events (by default known). While, as shown in Table 6.5 and Table 6.6, this scheme devises two different dedicated RHs separately for the FRC and Non-FRC events and consequently yields two different sets of *TMS* that, resulting, provide relatively more optimal protection compared to the conventional scheme. Thus, the intrinsic feature of the proposed scheme of providing the dedicated *HPMS*, RHs, and *TMS* avoids the protection latency which can happen due to the low fault current values, unnecessary constraints, and FRC failure events and thus makes the protection effectively faster. For e.g. in Table 6.5, the proposed scheme saves 87.3% of *Tr_sum* provided by the conventional method when R^{26d} relay is failed with FRC^{1} in islanding mode.

2. ***Rapid Protection***

The results of Table 6.5 and Table 6.6 show that, besides *Tr_sum*, this scheme reduces *T_conv* as well. Unlike in the conventional scheme, in the proposed scheme, T_conv is the part of the total fault clearing time as this scheme optimizes the settings by using online data after the fault occurence. It can be observed from the results that even after adding the convergence time with the *Tr_sum*, the total fault clearing time (which will be *Tr_sum*+*T_conv*) is significantly faster than the provided total fault clearing time by the conventional scheme which is equal to only *Tr_sum*. Thus, the proposed scheme provides faster protection without getting affected by the convergence time. Thus, it overall increases the speed of the protection compared to the conventional one.

3. ***Reliable protection in unknown fault situations (Communication Failures and Changes in operating mode)***

Next advantage of the proposed scheme is that unlike the existing adaptive schemes, it doesn't require the separate information related to the grid-connection and islanding mode, number, size, type, and ON/OFF status of DGs to select the relays settings from the pre-determined lookup table. The dedicated-protection feature of the scheme (as described in the point 1) makes the scheme capable of providing the protection in both known or unknown fault situations without being affected by the new installations or disconnections of the DGs and grid, and in the information loss due to FRC event.

4. ***Workable in both grid-connected and islanding operating mode***

In the presence of DGs, a Distribution system is exposed to a wide range of fault current levels. In grid-connected mode, the fault current level is significantly high compared to the islanding mode. The joint work of the proposed algorithms makes this scheme workable in both modes. The hybrid algorithm of determining the pickup setting makes this scheme able to pick up the relays in both modes by using the levels of other parameters besides the level of fault current. While the DFZD method makes this scheme able to detect a fault independent of the level of a fault current. Unlike the existing schemes [60], [93], [107] there is no need to implement different protection methods/strategies in order to provide the protection in various kinds of fault situation related to high or low fault impedance, symmetrical or unsymmetrical faults, radial or meshed configuration, and synchronous and asynchronous DGs.

5. ***Less complex and less congested communication-based protection design***

In the scenario of growing penetration of DGs, centralized protection schemes strengthen a protection scheme with their advantageous features of global and transparent decision making with less mutual data-sharing and less need of individual security of the communication links compared to the decentralized schemes [19], [20], [61]. The proposed scheme utilizes the centralized approach of the protection in which there is no need to send the statuses of measured parameters and operating mode continuously to the CPC by engaging the communication links all time as applied in [20], [105]. In this scheme, relays monitor the feeder line's parameters locally without engaging the links. Where the relays use their links to send their data only when they experience any triggering (positive or negative) of the *PS* signal. In this way, it frees the links during the normal situations for other transmission tasks and thus promotes a less congested and power-efficient communication structure.

6. ***Implementable or re-designable for the system where the relays are conventional or having no communication capabilities***

The proposed protection scheme (presented in chapter 6), which is the combination of all the proposed protection stages presented in the previous chapters, is designed assuming that the relays will be equipped with advanced features including data acquisition and communication capabilities. However, an active distribution system, where the protective devices are not equipped with advanced processing features and/or communication capabilities, can also be benefitted from the advantages of the individual proposed logics for different protection stages as described as follows.

a) If the relays, that have no communication facilities but have the capabilities to measure and process the parameters besides currents, can utilize the hybrid logic (from chapter 3) in detecting a fault locally in both grid-connected and islanding operating mode.

b) The algorithm for calculating the relays hierarchies (RHs) proposed in chapter 5 can be utilized in determining the pre-defined RHs (for the conventional relays) by using the pre-simulated pick up signals of the relays for different fault scenarios and zones. By using the proposed RHs algorithm (in Figure 5.3), unlike a conventional method, a man-free calculation for hierarchies of relays can be achieved.

c) By using the proposed CRRC logic in chapter 2, the offline settings using pre-simulated data can be determined and saved in the existing or microprocessor-based relays.

The summary and conclusion of the CAPS-1 scheme are given in Section (6.5).

6.3 PROTECTION SCHEME-2 (CAPS-2) CONSIDERING VARIABLE OPERATING MODES DURING BOTH NORMAL AND FAULTY CONDITIONS

The Protection Scheme-2 (CAPS-2) is designed for the system where change in an operating mode can happen due to change in the number and/or sizes of DGs in both normal and faulty conditions. Suppose, a system is planned for the maximum N_{DGmax} number of DGs (including DG1, DG2, … DG_{NDGmax}). Now, if, a fault occurs in an operating mode where only N_{DG} number of DGs out of N_{DGmax} DGs are currently active, then due to the disconnections of one or more DGs due to low FRT capabilities, the number of DGs during the fault can change. As a result, the devised relays settings may fail to prevail the relays coordination with changed number of DGs [93]. A comprehensive relay coordination (RC) approach, such as proposed in [18] and [99], devise the comprehensive relays settings by taking all the constraints corresponding to all possible operating modes due to change in the number of DGs. As per the documented research, the existing comprehensive RC approach is a good approach to solve the problem related to change in the number of DGs during a faulty condition. In this context, in the previous Chapter-2, a new comprehensive RC method, named as CRRC, has been proposed for the DGs-distribution system with variable operating mode. This method determines the optimal relays settings while taking a smaller number of constraints compared to the existing RC method [18], [99].

Now, along with the variability of the operating modes during normal and faulty conditions, the impact of the increasing proliferation of DGs on the protection scheme must also be considered. For this, this section first analyzes the performance of the CRRC relay coordination approach in the presence of increasing proliferation. Then, it proposes a modified CRRC method, named Smart Constraint Reduction Relay Coordination (SCRRC), which, by utilizing the gathered information from the system, not only will mitigates the investigated issues with CRRC but also will add some advantageous features to the protection approach. After that, in this section, the CAPS-2, comprised of the proposed SCRRC and the algorithms (Hybrid_algo, DFZD_algo, and RHs_algo) has been proposed.

Table 6.9
PERFORMANCE RESULTS FOR N_{DG}=2 IN CASE-B

	H=3			**H=2**		
Operating modes	**NDG_{max}=2 *(DG12)**	**NDG_{max}=3 *(DG123)**	**NDG_{max}=4 *(DG1234)**	**NDG_{max}=2 *(DG12)**	**NDG_{max}=3 *(DG123)**	**NDG_{max}=4 *(DG1234)**
	Tr_sum	*Tr_sum*	*Tr_sum*	*Tr_sum*	*Tr_sum*	*Tr_sum*
(DG1, DG2)	38.651	45.482	53.488	3.582	3.812	4.187
(DG1, 0)	39.186	47.987	55.632	8.409	8.781	9.738
(0, DG2)	54.07	62.203	72.088	7.207	7.488	8.352
Tr_sum_allM (s) for N_{DG}=2	131.906	155.672	181.207	19.199	20.081	22.277
Tot_constr	66	88	110	30	40	50
T_conv.(s)	0.1328	0.1575	0.1811	0.1075	0.1683	0.3577

*Denotes group of DGs for given N_{DGmax}; e.g. DG123 indicates that all DG1, DG2, and DG3 are connected.

6.3.1 Impact of the increasing proliferation of DGs on the performance of the CRRC

The CRRC method relaxes a number of operating modes compared to the conventional RC method while providing the comprehensive settings for the distribution system with variable number and sizes of DGs. This is shown in Section (2.3). Now, to explain the impact of the increasing proliferation of DGs, a case, named as Case-B, is taken here.

Case-B : When out of maximum planned DGs, NDG=2 i.e. only two DGs (DG1 and DG2) are in active state. Where in this case, due to disconnections of the DGs during the faulty condition, the system can appear in three possible operating modes [(DG1, DG2), (DG1, 0), and (0, DG2)].

In Table 6.9, the performance results of the CRRC method for N_{DG} =2 have been shown considering the presence of incremented N_{DGmax} (i.e. 2, 3, and 4). Where the performance has been shown in terms of the following parameters: *Tr_sum*, *Tr_sum_allM*, *T_conv*, and *Tot_constr*. Now, suppose, *H* is a number that represents the maximum level of RHs for which the settings need to be designed. For example: *H*=3 and H=2, where H=3 will include three sequential hierarchies (P, B1, and B2), while *H*=2 will include (P and B1).

It is observed from the obtained results in Table 6.9 that as the number of active DGs (i.e. N_{DG}) with respect to the planned maximum DGs' proliferation (N_{DGmax}) decreases, the performance of the existing CRRC method degrades. In addition, it has been observed in Table 6.9 that the degradation in the performance is more visible as the settings are optimized for the higher H value (i.e. from *H*=2 to *H*=3).

The next section presents a new RC method that overcomes the investigated demerits of the CRRC and further enhances the performance.

6.3.2 Smart Constraints Reduction Relay Coordination (SCRRC) Method

As per the CRRC method, discussed in the Section 2.3, the relays settings determined considering m_{max} and m_{min} proliferation successfully satisfy the protection coordination in all operating modes possible due to changes in the number of DGs. Moreover, in the presence of multiple operating sizes of a DG, the settings determined considering only two operating modes, related with maximum and minimum sizes of a DG, also successfully satisfy the protection coordination in all operating modes possible due to different operating sizes of a DG.

The proposed SCRRC method introduces some logic in the existing CRRC method by utilizing the information available from the system through a communication medium. In this work, the system is assumed to be equipped with advanced communication technologies and protective devices. In this scheme, three different sets of information, as described ahead, have been considered. The next subsections describe the methodology of the SCRRC method and how it overcomes the demerits of the CRRC method discussed in the previous section by utilizing the available information.

6.3.2.1 Information-1(info-1): Currently active DGs

By knowing which DGs are currently active, the present number of DGs in the current operating mode i.e. *NDG* will be known. By using this info-1, in the presence of the variable number and sizes of DGs, instead of taking N_{DG}^{max} as m_{max}, the SCRRC takes *NDG*. Similarly, for m_{min} which is equal to 1, it only counts the operating modes possible due to changes in the number and sizes of only the active *NDG* DGs instead of all N_{DG}^{max} DGs. The general expressions for the T^{modes} and *OF* in the presence of info-1 are given in Equation (6.1) and Equation (6.2) respectively, where '2' integer denotes the number of operating modes associated with the maximum and minimum sizes of an i^{th} DG. In these equations, the full expression of *Tr_sum* can be found in (2.6). The SCRRC with info-1 uses near-end and far-end fault offline values.

$$\begin{aligned} \mathrm{T}_{SCRRC}^{\mathrm{mod}\,es(\mathrm{info1})} &= \left[\sum_{m=1}^{C_1^{N_{DG}}} (2) \right]_{m_{\min}} + \left[\prod_{i=1}^{N_{DG}} (2) \right]_{m_{\max}} \\ &= \left[2 \times N_{DG} \right]_{m_{\min}} + \left[2^{N_{DG}} \right]_{m_{\max}} \end{aligned} \tag{6.1}$$

$$OF_{SCRRC}^{\text{info-1}} = \left[\sum_{sm=1}^{2^{N_{DG}}} (\text{Tr\_sum}) \right]_{m_{\min}} + \left[\sum_{sm=1}^{2^{N_{DG}}} (\text{Tr\_sum}) \right]_{m_{\max}} \quad (6.2)$$

Table 6.10
SELECTION OF OPERATING MODES BY SCRRC METHOD (WITH INFO-1) FOR CASE-A WITH VARIABLE DGS SIZES

m	**DG1 (n_{s1})**	**DG2 (n_{s2})**	**DG3 (n_{s3})**	**Total Combinations For a *sm***	**A***	**T^{modes} for a *m***
m_{min}=1	**2**	**0**	0	2	A1	(A1+A2)
	0	**2**	0	2	A2	
	0	0	2	-	-	
m_{max}=2	**2**	**2**	0	4	A7	A7

*A denotes a variable that represents the number of combinations of operating modes

Table 6.11
SELECTION OF OPERATING MODES BY THE SCRRC METHOD (WITH INFO-2) FOR CASE-A WITH VARIABLE DGS SIZES

m	**DG1 (n_{s1})**	**DG2 (n_{s2})**	**DG3 (n_{s3})**	**Total Combinations For a *sm***	**A**	**T^{modes} for a *m***
m_{min} =1	**1**	**0**	0	1	A1	(A1+A2)
	0	**1**	0	1	A2	
	0	0	1	-	-	
m_{max}=2	**1**	**1**	0	1	A7	A7

The SCRRC methodology with info-1 can be explained by using a **Case-A which** is as below:

Case-A: {When a maximum 3 DGs (DG1, DG2, and DG3) with variable sizes are connected in the system i.e N_{DG}^{max} =3, and NDG=2 (DG1 and DG2). }

In this case, the CRRC will select all the operating modes shown in bold font in Table 2.1**.** Now, if in the current operating mode, only two DGs i.e. DG1 and DG2 are detected as active while DG3 is detected inactive. The CRRC will again select the same operating modes as shown in bold font in Table (2.1). Whereas, the SCRRC will select the operating modes, which are shown in the shaded are of Table 6.10, where, m_{min} =1 and m_{max} = N_{DG} =2. Thus, according to Equation (6.1), SCRRC will take only 8 operating modes whereas the CRRC will take 14 operating modes as shown in Equation (2.11).

6.3.2.2 Information-2 (info-2): Operating sizes of the active DGs including info-1

If besides the active DGs (i.e. info-1), their operating sizes are also known, then by utilizing this information, instead of two operating modes that are related to maximum and minimum sizes of an i^{th} active DG, the SCRRC will select only one operating mode i.e. *sm_current*

$$\mathrm{T}_{SCRRC}^{\mathrm{mod}\,es(\mathrm{info}\,2)} = \left(\sum_{m=1}^{C_1^{N_{DG}}} (1) \right)_{m_{\min}} + \left(\prod_{i=1}^{N_{DG}} (1) \right)_{m_{\max}}$$
$$= \left(N_{DG} \right)_{m_{\min}} + \left(1\right)_{m_{\max}} \tag{6.3}$$

$$OF_{SCRRC}^{\text{info-2}} = \left[\sum_{sm=1}^{N_{DG}} (\mathrm{Tr\_sum}) \right]_{m_{\min}} + \left[Tr\_sum \right]_{sm^{current}} \tag{6.4}$$

corresponding to the current operating size of the DG.

The general expressions for the T^{modes} and *OF* in the presence of info-2 are presented in Equation (6.3) and Equation (6.4) respectively. To explain, for the Case-A discussed in just above sub-section, in the presence of info-2, the selection of m_{min} and m_{max} values will be the same 1 and 2 respectively. But the selection and number of related *sm* operating modes will be different, which can be seen in the shaded area of Table 6.11. In Table 6.11, the values of A1, A2, and A7 get changed compared to the values given in Table 6.10. Thus, compared to the 8 modes (as shown in Table (6.10) as taken by the SCRRC with info-1. The SCRRC with info-2, only 3 operating modes (as shown in Table (6.11) will be taken to determine the comprehensive settings.

6.3.2.3 With Information-3 (info-3): Fault current values in the current operating mode (including info-1 and info-2))

By utilizing the fast communication technologies and advanced relay's features such as data acquisition, multifunctioning, data communication, and numeric calculations, the fault current values can be updated to the CPC. With this information, the T^{modes} will be the same as given in Equation (6.3), while the OF is given in Equation (6.5) where W^{sm} is taken from Equation (2.7). The first term of the Equation (6.5) is same as of the first term of the Equation (6.4) where it uses offline based near-end and far-end fault values. While the second term is different from the second term of Equation (6.4) where it uses only present online fault values. Thus, in the presence of info-3, the relays coordination will be the combined result of the offline and online fault values. To show the effectiveness of the SCRRC with info-3, compared to the conventional [99] and CRRC methods, the T^{modes} for two different N_{DG}^{max} and NDG combinations are shown in Table 6.12**.** This table explains that as the difference between the N_{DG}^{max} and NDG increase, the effectiveness of the SCRRC becomes more visible.

Table 6.12
TOTAL OPERATING MODES SELECTED BY DIFFERENT METHODS

Configuration of N_{DG}^{max} and NDG	Total number of operating modes		
	Conv.	CRRC	SCRRC
$N_{DG}^{\max}=3$, $N_{DG}=2$	7	4	3
$N_{DG}^{\max}=10$, $N_{DG}=4$	1023	11	5

$$OF_{SCRRC}^{\text{info-3}} = \left[\sum_{sm=1}^{N_{DG}} (\text{Tr\_sum})\right]_{m_{\min}} + \left[\sum_{p=1}^{P_Z^{sm}} W^{sm^{current}}\right]_{\substack{\text{present fault}\\\text{data}}} \tag{6.5}$$

6.3.3 Comparative Performance of the SCRRC

6.3.3.1 Simulation Setup

The performance of the SCRRC method is demonstrated using the meshed configuration of the IEEE 38-bus distribution system as shown in Figure 2.1. Four DGs (DG-1, DG-2, DG-3, and DG-4) are connected at the buses 26, 9, 24, and 29 respectively. The short circuit MVA capacity of each DG is 5 times its rated unit. This study has been conducted in the environment of Matlab simpower systems toolbox and coding, while the optimization process has been done using the linear optimization tool in Matlab. It is assumed that the modern relays will be equipped with advanced signal processing units and communication technologies, and will be able to compare the fault current direction with the direction of the *FDb* as described in the Section (4.2.1). Two fault events as explained below is taken for obtaining the results:

Fault-event (A): A LLLG fault with *Rf* = 3.5ohm and *Rg*=50ohm occurs on the z7 feeder zone in Grid connected meshed test system.

Fault-event (B): An LLLG fault occurs at the z29 with *Rf*=1.5Ω and *Rg*=50Ω.

The results of Fault-event (A) are shown in Table 6.13, Table 6.14, and Table 6.17. While in Table 6.15, the results for both Fault-event (A) and a Fault-event (b) are shown. To show the individual effectiveness of the SCRRC on the relay performance, the results are compared on the same ground where conventional *PSM*, RHs selection, and formula for operating time have been taken from the Section (1.2). While the values of characteristics constants that are A, B, and c are taken as 80, 0, and 1 respectively. In this study, the minimum limit of *TMS* and *CTI* are taken as 0.001 and 0.3s respectively.

The results have been obtained for the cases when the number of DGs in the current operating mode (N_{DG}) with respect to the planned maximum number of DGs (N_{DGmax}) is less. The comparison has been made in terms of the *Tr_sum*, *Tr_sum_allM*, *T_conv*, and *Tot_constr* parameters. While conducting the comparison study, the results have been obtained for two different maximum relay hierarchies H=3 and H=2 (as described in Section (6.3.1)).

Table 6.13
OPERATING MODES POSSIBLE WITH 4 DGS

	M1	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**	**M9**	**M10**	**M11**	**M12**	**M13**	**M14**	**M15**
DG1	1	1	0	0	0	1	0	0	1	0	1	1	0	1	1
DG2	1	0	1	0	0	1	1	0	0	1	0	0	1	1	1
DG3	1	0	0	1	0	0	1	1	0	0	1	1	1	0	1
DG4	1	0	0	0	1	0	0	1	1	1	0	1	1	1	0

b) Obtained Results and Comparison

Scenario-1: When only the number of DGs are variable

To show the results for this scenario, the size of each DG is taken fixed 3 MVA. By knowing the sizes of active DGs, info-2 will be known. Now, if the CPC receives online present fault current values, then the info-3 will be known. The performance of the SCRRC is explained using a case, named Case-1 which is described as follows.

Case-1: In Case-1, N_{DGmax} is assumed 4 (N_{DGmax} = 4) which means maximum of four DGs (DG1, DG2, DG3, and DG4) can operate simultaneously in the system. So, as shown in Table 6.13, total 15 operating modes (M1 to M15) can be possible with these 4 DGs. Now, if a fault occurs in the current operating mode where (N_{DG} = 3) only three DGs (DG2, DG3, and DG4) are in active state, so, due to the disconnection of DGs during the faulty condition, the system can appear in anyone of the operating mode from total 7 different possible operating modes as shown in first column of Table 6.14.

Now, to protect the system from the fault in variable operating modes, both methods (CRRC and SCRRC) provide comprehensive settings by using the fault data corresponding to their selected operating modes. The CRRC selects (M2, M3, M4, and M5) operating modes for m_{min}, and (M1) operating mode for m_{max} conditions. On the contrary, the SCRRC relaxes number of operating modes and selects comparatively fewer operating modes which includes (M3, M4, and M5) for m_{min} and (M13) for m_{max} conditions with both info-2 and info-3.

Table 6.14

COMPARATIVE PERFORMANCE RESULTS OF SCRRC FOR SCENARIO-1, CASE-1: {*NDG*=3 (DG2,3,4), N_{DGmax} =4 (DG1,2,3,4), FAULT-EVENT(A)}

Op_ modes	**H=3**			**H=2**		
	CRRC	**SCRRC**		**CRRC**	**SCRRC**	
		Info-2	**Info-3**		**Info-2**	**Info-3**
	Tr_sum	*Tr_sum*	*Tr_sum*	*Tr_sum*	*Tr_sum*	*Tr_sum*
M13	44.704	36.297	32.256	4.207	4.353	3.609
M7	39.109	38.605	36.446	4.821	4.497	3.773
M10	38.859	37.352	33.358	7.159	4.747	3.946
M3	72.087	68.443	60.717	8.352	7.805	6.298
M8	25.776	25.208	20.574	4.576	4.619	3.251
M4	31.041	30.029	25.025	5.383	5.371	3.897
M5	25.087	24.432	20.077	4.149	4.194	2.975
Tr_sum_allM (s)	276.663	262.465	228.452	38.649	35.587	27.749
%Red.*		5.13%	17.43%		7.92%	28.20%
Tot_constr	110	88	77	50	40	35
T_conv (s)	0.224	0.144	0.066	0.211	0.144	0.062

*Achieved % reduction in *Tr_sum_allM* with respect to the CRRC.

The comparative results for Case-1 is shown in table 6.14. The results show that the SCRRC overall relaxes a significant number of constraints and yields optimal settings in shorter optimization convergence time (*T_conv*) compared to the CRRC. In addition, it can also be noticed that the SCRRC provides reduced *Tr_sum* and *Tr_sum_all* and clears the fault significantly faster than by the CRRC. To further testify the performance, the results have also been obtained for one more case, named Case-2, which is given below.

Case-2: {N_{DG}=2 (DG1,2), N_{DGmax} = 4 (DG1,2,3,4)}. If a fault occurs in the current operating mode where only two DGs (DG1 and DG2) are in active state, so, due to the disconnection of DGs during the faulty condition, the system can appear in anyone of the operating mode from possible operating modes given in the first column of Table 6.15.

The results for Case-2 are shown in Table 6.15 which further verify the above-described

Table 6.15
COMPARATIVE PERFORMANCE RESULTS OF SCRRC FOR SCENARIO-1 CASE-2: {*NDG*=2 (DG1,2), N_{DGmax} =4 (DG1,2,3,4), FAULT-EVENT(A)}

op modes	**H=3**			**H=2**		
	CRRC	**SCRRC**		**CRRC**	**SCRRC**	
		Info-2	**Info-3**		**Info-2**	**Info-3**
	Tr_sum	*Tr_sum*	*Tr_sum*	*Tr_sum*	*Tr_sum*	*Tr_sum*
M6 (11)	53.487	38.651	21.005	4.1871	3.582	2.113
M2 (10)	55.631	39.185	21.920	9.737	8.409	4.451
M3 (01)	72.088	54.070	27.671	8.3523	7.207	3.499
Tr_sum_allM (s)	181.207	131.905	70.595	22.277	19.198	10.063
%Red.*		27.21%	61.04%		13.82%	54.83%
Tot_constr	110	66	55	50	30	25
T_conv (s)	0.181	0.133	0.039	0.168	0.108	0.039

Achieved % reduction in Tr_sum_*allM with respect to the CRRC.

Table 6.16
SOME OPERATING MODES FOR VARIABLE SIZE DGS IN CASE-3

Modes	**M1'**	**M2'**	**M3'**	**M4'**	**M5'**	**M6'**	**M7'**	**M8'**	**M9'**	**M10'**	**M11'**	**M12'**	**M13'**
DG1	3	3	3	3	3	0	0	0	0	0	3	3	3
DG2	5	5	3	3	0	5	3	0	0	4	4	3	5
DG3	5	3	5	3	0	0	0	5	3	0	0	0	0

advantages of the SCRRC.

Now, the impact of the type of information on the performance of the SCRRC can also be observed from these tables, where it can be observed that compared to info-2, the SCRRC provides more efficient and fast performance with info-3. This occurs because of the relaxation of the constraints and employment of the online data while setting up the relays. Due to which, it provides relatively more optimal settings. For example: in the results of Case-2 as shown in Table 6.15'; with info-3, the SCRRC provides approx. 47% reduction in the *Tr_sum _allM* compared to info-2 with H=3.

Table 6.17
COMPARATIVE PERFORMANCE RESULTS OF SCRRC FOR SCENARIO-2 CASE-3: {N_{DG} =2 (DG1,2), N_{DGmax} =3, (DG1,2, 3)}

Operating modes	**H=3**				**H=2**			
	CRRC	**SCRRC**			**CRRC**	**SCRRC**		
		Info-1	**Info-2**	**Info-3**		**Info-1**	**Info-2**	**Info-3**
	Tr_sum	*Tr_sum*	*Tr_sum*	*Tr_sum*	*Tr_sum*	*Tr_sum*	*Tr_sum*	*Tr_sum*
****Fault-event (A):**								
M5'	54.567	43.709	40.487	22.467	9.684	9.219	8.833	4.553
M10'	68.554	59.433	54.487	27.570	8.058	7.715	7.324	3.497
M11'	51.776	43.539	39.865	21.545	4.049	3.799	3.664	2.127
Tr_sum_allM (s)	174.898	146.682	134.841	71.584	21.791	20.734	19.821	10.178
*%Red.		16.132%	22.90%	59.07%		4.85%	9.04%	53.29%
Tot_constr	198	110	66	55	90	50	30	25
T_conv (s)	0.8186	0.3348	0.115	0.0381	0.7373	0.2665	0.0961	0.0315
****Fault-event (B):**								
M5'	39.118	26.372	25.590	19.936	6.176	4.987	4.8552	4.1349
M10'	16.939	13.051	12.623	9.461	2.787	2.224	2.1755	1.9277
M11'	23.479	14.541	14.171	11.89	3.249	2.569	2.5257	2.3324
Tr_sum_allM (s)	79.536	53.964	52.384	41.284	12.212	9.781	9.5565	8.395
*%Red.		32.16%	34.14%	48.09%		19.91%	21.74%	31.26%
Tot_constr	154	86	52	43	90	50	30	25
T_conv (s)	0.2663	0.1477	0.0973	0.034	0.2363	0.1432	0.0825	0.4365

*Achieved % reduction in *Tr_sum_allM* with respect to the CRRC. **Given in Section 6.3.3

Scenario-2: When both the number and sizes of DGs are variable

To explain the performance in this scenario, a Case-3 has been taken, which is as follows.

Case-3: In this case, a fault occurred when only 2 DGs (DG1 and DG2) are active in the system while N_{DGmax} =3. Here, the size of DG1 is fixed at 3MVA while the size of DG2 and DG3 can vary in three different sizes (3, 4, and 5 MVA). With these variable sizes of DGs, a total 31 operating modes will be possible as per Equation (2.2).

The comparative performance for Case-3 has been shown in Table 6.17. Where, to show the performance, instead of all 31 operating modes, a sub-set of the total operating modes have been taken. To determine the comprehensive settings for this sub-set, different methods select different operating modes from Table 6.16, which is discussed below:

Conventional: {M1' to M13'}; CRRC: {M1' to M9'}; $SCRRC_{info\text{-}1}$: {M5', M6', M7', M12', M13'}, $SCRRC_{info\text{-}2 \text{ and } info\text{-}3}$: {M5', M10', M11'}. The performance has been investigated for all the possible operating modes with N_{DG} =2 when DG2 is operating at its intermediate size 4MVA and DG1 is operating at its fixed size 3MVA. The results of Table 6.17 show that the SCRRC provides significantly reduced *Tr_sum*, *Tr_sum _allM*, *T_conv, and Tot_constr* compared to the CRRC, and likewise in the scenario-1, it speeds up the protection efficiently in this scenario also. In addition, as the CPC gets more information, more enhancement in the performance of the SCRRC can be noticed.

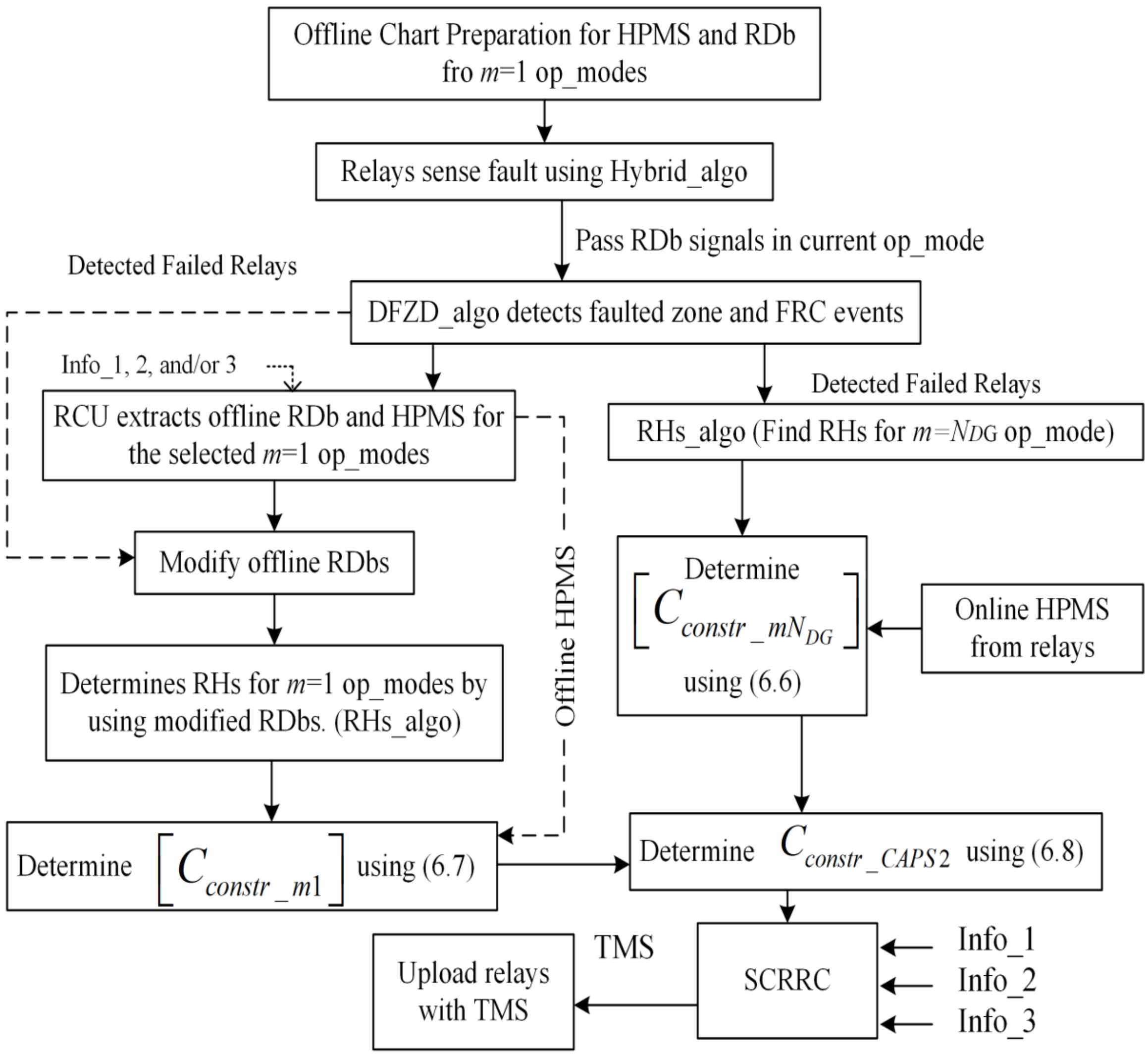

Figure 6.5 Workflow of the CAPS-2

6.3.4 Workflow of the Comprehensive Adaptive Protection Scheme-2 (CAPS-2)

The workflow of the CAPS-2 is shown in Figure 6.5. As figure shows, this scheme is the amalgamation of the algorithms Hybrid_algo, DFZD_algo, RHs_algo and SCRRC proposed in the previous chapters. The functioning of this scheme is divided into the two main stages as explained below.

- **Stage-1: Offline Calculations at RCU**

In this stage, by performing the offline simulation, the RCU calculates and stores the offline values of the relays' *HPMS* for both near-end and far-end faults for a zone. In addition, it also calculates and stores *RDb* signals for all operating modes (sm) that are possible with m_{min} i.e. m=1. Now, suppose, in an Example 6.1, if in a system, N_{DGmax} = 10, then out of the total $\sum_{m=1}^{10} C_m^{10}$ possible operating modes, offline data associated with only $C_1^{10} = 10$ operating modes need to be stored.

- **Stage-2: Online Processing at RCU**

Stage 2(a): ***Determine adaptive RHs***: When a fault will occur, the RCU will receive *RDb* and *HPMS* signals from relays in the current operating mode (sm_current). Then, by using these collected *RDb*, the RCU will detect the faulted zone and failed relays with FRC (if happens) by using the DFZD-algo as explained in Section (4.3)**.** After this, it modifies the offline *RDb* bits corresponding to the selected operating modes, by utilizing the information about the online detected failed relays with FRC. Where it makes all the *RDb* bits zero that associated relays are detected failed with FRC. Now, in the above-discussed Example 6.1, as per the info-

1, if NDG=4, then, instead of $C_1^{10} = 10$ operating modes, the CAPS-2 will modify the RDb bits for only 4 operating modes. This can also be seen in Table 6.18. Then, by using these

Table 6.18

Online Modification in offline RDb bits

	R1	R2	R3	R4	R5	R6
RPD	+1	+1	+1	-1	0	-1
Working Status	W	W	**FRC**	W	W	**FRC**
Modified RPD	+1	+1	0	-1	0	0

modified *RDb* bits, it determines the RHs by using the RHs_algo as explained in Section (5.3), for the selected operating modes with *m*=1. At the same time, it also determines the RHs for the current operating mode by using the online RDbs.

The selection of the operating mode for m=1 can be explained as follows. In the above-mentioned Example-6.1, out of $C_1^{10} = 10$ DGs (DG1, DG2….DG10), if only 4 DGs (DG1 to DG4) are in the active state, then operating mode with *m*=1 in which only these 4 DGs ($C_1^{4} = 4$) are present will get selected while rest of the operating modes get excluded.

Stage 2(b): ***Determine Constraints and TMS***: Then, based on the determined RHs, it composes the constraints matrices, $C_{constr\_mN_{DG}}$ and C_{constr_m1}, for the selected operating modes corresponding to m_{min} (=m1) and m_{max} (=m_{NDG}) respectively. These matrices are shown in Equation (6.6) and Equation (6.7) respectively, where these are calculated by using the offline and online HPMS values respectively. Then after, a single matrix is constructed by using these matrices, as shown in Equation (6.8). In the next step, the scheme determines the optimal TMS for the relays by using the SCRRC relay coordination in the presence of available information, as explained in the Section (6.3.2). Where relay operating time is shown in Equation (3.5). After that, the RCU sends the optimal TMS to the associated relays. The operation of the relay tripping and upgrading process of the RCU by using the ‘C’ and ‘PS’ signals is described using the block-diagram (shown in Figure (6.2)) explained in Section (6.2.1 (d)).

$$\left[C_{constr\_mN_{DG}}\right]=\left[C_{constr\_DG_{(1,2,3,4\ \text{and}\ \text{NDG})}}\right] \tag{6.6}$$

$$\left[C_{constr\_m1}\right]=\left[C_{constr\_DG_1}\quad C_{constr\_DG_2}\quad C_{constr\_DG_3}\quad C_{constr\_DG_4}\quad .\quad .\quad C_{constr\_DG_{NDG^{th}}}\right]^T \tag{6.7}$$

$$(C_{constr\_CAPS2})=\begin{bmatrix} C_{constr\_m1} \\ C_{constr\_mN_{DG}} \end{bmatrix} \tag{6.8}$$

6.3.5 Comparative Performance of the CAPS-2

The effectiveness of the CAPS2 has been shown by using the comparative results obtained for two different cases Case-A1 and Case-A2 as described below:

- **Description of Case-A1: When the only number of DGs is variable**

In this case, the Fault-event-A (as described in Section (6.3.3.1)) at the z7 zone happens in the system where only number of DGs are variable and DGs’ sizes are fixed. While NDG_{max}=3 and NDG=2, where, out of maximum three DGs (DG1, DG2, and DG3), only two DGs (DG1 and DG2) are in active state in the system. At the same time, R7u and R7d end-relays are failed to send the relevant information due to FRC. For this case, conventional selects {M15, M11, M7, M6, M4, M3, and M2} operating modes while $SCRRC_{info-3}$ selects only {M6, M3, M2} from Table 6.13.

- **Description of Case-A2: When both the number and size of DGs are variable**

In this case, the same Fault-event-A at z7 zone happens in the system when both the number and sizes of DGs are variable. While N_{DGmax}=3 and N_{DG} =2 (DG1 and DG2) and the same FRC failed relays R7u and R7d. In this case, conventional selects {M1' to M13'} operating modes while $SCRRC_{info-3}$ selects only {M11', M10', M5'} from Table 6.16'.

TABLE 6.19
Comparative Performance of CAPS-2 in Case-A1

Modes for *NDG* From Table 6.13	Calculated Parameters	Conv	CAPS-2	% reduction in Val-2 w.r.t Val-1
		(Val-1)	(Val-2)	
M6 (1 1 0)	*Tr_sum (s)*	52.6607	2.0821	96.046%
M3 (0 1 0)	*Tr_sum (s)*	68.8788	3.1167	95.475%
M2 (1 0 0)	*Tr_sum (s)*	58.0309	3.9369	93.215%
	Tr_sum_allM (s)	179.5704	9.1357	94.912%
	Tot_constr	154	30	80.519%
	T_conv (s)	0.0508	0.0088	82.677%

TABLE 6.20
Comparative Performance of CAPS-2 in Case-A2

Modes for *NDG* From Table 6.16'	Calculated Parameters	Conv	CAPS-2	% reduction in Val-2 w.r.t Val-1
		(Val-1)	(Val-2)	
M11' (3 4 0)	*Tr_sum (s)*	53.8110	3.0615	94.311%
M10' (0 4 0)	*Tr_sum (s)*	46.6257	5.3492	88.527%
M5' (3 0 0)	*Tr_sum(s)*	30.7992	6.5948	78.587%
	Tr_sum_allM (s)	131.2359	15.0055	88.566%
	Tot_constr	286	54	81.118%
	T_conv (s)	0.0763	0.0125	83.617%

The results for Case-A1 and Case-A2 are shown in Table 6.19 and Table 6.20 respectively. The results of both tables show that, compared to the conventional scheme, the CAPS-2 with info-3 can provide a very effective reduction (around 80-95%) in all *Tr_sum*, *Tr_sum_allM*, *Tot_constr*, and *T_conv* in both the current operating mode (when two DGs are active) and the operating modes which can appear if DGs get disconnected during the fault condition.

The summary and conclusion of this CAPS-2 scheme can be seen in Section (6.5).

6.4 Cumulative Performance of The Proposed Algorithms in CAPS

The individual roles of each proposed-algorithms in making CAPS-1 and CAPS-2 protection schemes faster are shown for two cases, Case-A1 and Case-A2, as described in Section 6.3.5. Where, Case-A1 represents the scenarios where only number of DGs is variable, while Case-A2 represents the scenarios where both number and sizes of DGs are variable. The results are shown in Table 6.21 to Table 6.24. The comparative performance has been investigated in terms of the *Tr_sum*, *T_conv*, *Td_HMPS*, *Td_RHs*, *Tot_algos*, *Tot_FCT*,

Where,

$$Tot\_algos = (Td\_DFZD + Td\_HMPS + Td\_RHs + T\_conv) \quad (6.9)$$

$$Tot\_FCT = (Td\_algos + Tr\_sum) \quad (6.10)$$

The results show that each algorithm has its own significant contribution in making the proposed protection schemes faster. Moreover, it can also be observed that even after the addition of online *Tot_algos* delay, proposed schemes provide much faster protection compared to the conventional scheme. For example, with CAPS-1, 97.76% reduction in *Tot_FCT* can be achieved in Case-A1 in the presence of two FRC failed relays (FRC^2).

Table 6.21

Cumulative Performance of The Proposed Algorithms in CAPS-1

When only number of DGs is variable (Case-A1)

Modes for N_{DG}=2	**Conv** (With PMSold, RHs_old)	**CRRC** (With PMSold and RHs_old)	**CAPS-1** **+HPMS*** (With RHs_old)	**CAPS-1** **+RHs_new***	**CAPS-1** **+FRC[1]**** **(R7u)**	**CAPS-1** **+FRC[2]**** **(R7u and R7d)**
M6 (1 1 0)	52.660	45.481	5.730	3.540	2.910	1.155
M3 (0 1 0)	68.878	62.203	5.934	3.686	3.047	1.361
M2 (1 0 0)	58.030	47.987	6.135	3.830	3.208	1.365
Tr_sum_allM for these modes (s)	179.570	155.672	17.799	11.057	9.166	
Tot_constr.	154	88	M6: 11 M3: 11 M2: 11	8 8 8	7 7 7	6 6 6
T_conv (s)	0.0508	0.0310	M6: 0.0144 M3: 0.0126 M2: 0.0149	0.0129 0.0130 0.0101	0.0130 0.0132 0.0094	0.0132 0.0204 0.0136
Online *Td_HPMS* (s)	NA (as offline)	NA (as offline)	M6: 0.0016 M3: 0.00033 M2: 0.0015	0.0016 0.0017 0.00031	0.0016 0.0016 0.00034	0.0019 0.0018 0.00044
Online *Td_RHs* (s)	NA (as offline)	NA (as offline)	M6: 0.0011 M3: 0.00062 M2: 0.0013	0.0015 0.0015 0.00078	0.0014 0.0013 0.00056	0.0024 0.0024 0.0026
Online *Td_DFZD* (s)	NA (as offline)	NA (as offline)	0.0020	0.0020	0.0023	0.0025
Online *Td_Algos* (s)	NA (as offline)	NA (as offline)	0.019	0.018	0.018	0.0195
Tot_FCT in M6 (s)	52.661	45.482	5.749	3.558	2.928	1.175
%Red ***	-	**13.633%**	**87.359%**	**38.113%**	**17.707%**	**59.877%**

*Faulted zone by using DFZD_algo **Faulted zone and failed relays is detected by using DFZD_algo
*** % Reduction achieved in the subsequent stage w.r.t. the previous stage

Table 6.22

Cumulative Performance of The Proposed Algorithms in CAPS-1 When both number and sizes of DGs are variable (Case-A2)

Modes for N_{DG}=2	**Conv (**With *PMSold*, *RHs_old***)**	**CRRC (**With *PMSold* and *RHs_old***)**	CAPS-1				
			+HPMS* (With *RHs_old***)**		**+RHs***	**+FRC-1** (R7u)**	**+FRC-2** (R7u and R7d)**
M11' (3 4 0)	53.8110	53.5225	5.7300		3.5400	2.9100	1.1485
M10' (0 4 0)	46.6257	46.4442	5.9252		3.6799	3.0407	1.3418
M5' (3 0 0)	30.7992	30.6774	6.1353		3.8309	3.2088	1.3661
Tr_sum_allM for these modes (s)	131.2359	130.6441	17.7905		11.0508	9.1595	3.8564
Tot_constr.	286	198	M11 M10 M5	11 11 11	8 8 8	7 7 7	6 6 6
T_conv (s)	0.0763	0.0600	M11 M10 M5	0.0130 0.0152 0.0122	0.0129 0.0123 0.0099	0.0127 0.0124 0.0098	0.0143 0.0131 0.0100
Online *Td_HPMS* (s)	NA (as offline)	NA (as offline)	M11 M10 M5	0.0016 0.0017 0.00038	0.0016 0.0017 0.00032	0.0017 0.0017 0.00029	0.0020 0.0017 0.00028
Online *Td_RHs* (s)	NA (as offline)	NA (as offline)	M11 M10 M5	0.00093 0.00088 0.00099	0.0016 0.0012 0.00055	0.0013 0.0012 0.0006	0.0020 0.0017 0.0012
Online *Td_DFZD* (s)	NA (as offline)	NA (as offline)	0.0020	0.0020	0.0020	0.0023	0.0025
Online *Td_Algos* (s)	NA (as offline)	NA (as offline)	0.018		0.018	0.019	0.021
Tot_FCT in M11 (s)	53.8110	53.5225	5.748		3.558	2.930	1.170
%Red ***		**0.536136**	**89.26059**		**38.10021**	**17.70658**	**60.07514**

*Faulted zone by using DFZD_algo **Faulted zone and failed relays is detected by using DFZD_algo
*** % Reduction achieved in the subsequent stage w.r.t. the previous stage

Table 6.23

Cumulative Performance of The Proposed Algorithms in CAPS-2

When only number of DGs is variable (Case-A1)

Modes for N_{DG}=2	**Conv (**With *PMSold*, *RHs_old***)**	**CRRC (**With *PMSold*, *RHs_old***)**	**CAPS-2 (With SCRRC)**				
			+HPMS* (With *RHs_old***)**	**+RHs***	**+FRC-1** (R7u)**	**+FRC-2** (R7u and R7d)**	**Info-3**
M6 (1 1 0)	52.6607	45.4816	30.6996	13.4992	11.7766	3.1062	2.0821
M3 (0 1 0)	68.8788	62.2032	37.8307	20.3194	17.7045	5.5206	3.1167
M2 (1 0 0)	58.0309	47.9875	31.2644	23.3612	18.3491	6.5812	3.9369
Tr_sum_allM for these modes (s)	179.5704	155.6723	99.7947	57.1798	47.8302	15.208	9.1357
Tot_constr	154		66	48	42	36	30
Online *T_conv* (s)	0.0508		0.0169	0.0090	0.0132	0.0121	0.0088
Online *Td_HPMS* (s)	NA (as offline)	NA (as offline)	0.00029	0.00034	0.00027	0.00030	0.00035
Online *Td_RHs* (s)	NA (as offline)	NA (as offline)	0.00068	0.00060	0.00056	0.0011	0.0010
Online *Td_DFZD* (s)	NA (as offline)	NA (as offline)	0.0020	0.0020	0.0020	0.0023	0.0025
Online *Td_Algos* (s)	NA (as offline)	NA (as offline)	0.020	0.012	0.016	0.016	0.013
Tot_FCT in M6 (s)	**52.6607**	**45.4816**	**30.7196**	**13.5112**	**11.7926**	**3.1220**	**2.0948**
%Red.		**13.63275**	**32.45708**	**56.01766**	**12.71982**	**73.52407**	**32.9287**

*Faulted zone by using DFZD_algo **Faulted zone and failed relays is detected by using DFZD_algo
*** % Reduction achieved in the subsequent stage w.r.t. the previous stage

Table 6.24

Cumulative Performance of The Proposed Algorithms in CAPS-2

When both number and size of DGs are variable (Case-A2)

Modes for N_{DG}=2	**Conv (**With *PMSold*, *RHs_old***)**	**CRRC (**With *PMSold*, *RHs_old***)**	**CAPS-2 (With SCRRC)**				
			+HPMS* (With *RHs_old***)**	**+RHs***	**+FRC-1** (R7u)**	**+FRC-2** (R7u and R7d)**	**Info-3**
M11 (3 4 0)	53.8110	53.5225	34.2287	15.1522	13.4082	3.2835	3.0615
M10 (0 4 0)	46.6257	46.4442	42.0894	22.6433	20.0001	5.9551	5.3492
M5 (3 0 0)	30.7992	30.6774	34.6055	26.1351	21.0967	7.1842	6.5948
Tr_sum_allM for these modes (s)	131.2359	130.6441	110.9236	63.9306	54.505	16.4228	
Tot_constr	286	198	110	80	70	60	54
Online *T_conv* (s)	0.0763	0.0600	0.0437	0.0228	0.0272	0.0309	0.0125
Online *Td_HPMS* (s)	NA	NA	0.000319	0.00034	0.000454	0.000312	0..000303
Online *Td_RHs* (s)	NA	NA	0.0028	0.0046	0.0044	0.0044	0.0048
Online *Td_DFZD* (s)	NA (as offline)	NA (as offline)	0.0020	0.0020	0.0020	0.0023	0.0025
Online Td_Algos (s)	NA (as offline)	NA (as offline)	0.049	0.030	0.034	0.038	0.020
Tot_FCT in M11 (s)	53.8110	53.5225	34.2777	15.1822	13.4422	3.3215	3.0815
%Red.		**0.536136**	**35.95647**	**55.70823**	**11.46079**	**75.2905**	**7.225651**

*Faulted zone by using DFZD_algo **Faulted zone and failed relays is detected by using DFZD_algo

*** % Reduction achieved in the subsequent stage w.r.t. the previous stage

- The overall impact of the proposed schemes (CAPS-1 and CAPS-2) on the total fault clearing time for the taken cases Case-A1 and Case-A2 is summarized in Figure (6.6a) and Figure (6.6b).

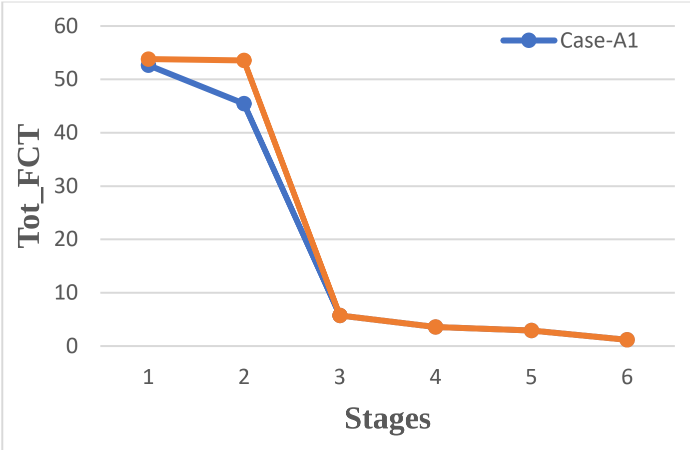

Table 6.25

Description of Stages shown in Figure 6.6(a)

Stage1	Conv.
Stage2	CRRC
Stage3	CAPS1,+Hybrid_algo
Stage4	Stage3+RHs_algo
Stage5	Stage4+FRC1 by DFZD
Stage6	Stage5+FRC2 by DFZD

Figure 6.6(a) Reduction by CAPS-1 in total fault clearing time (*Tot_FCT*) in different stages (as described in Table 6.25).

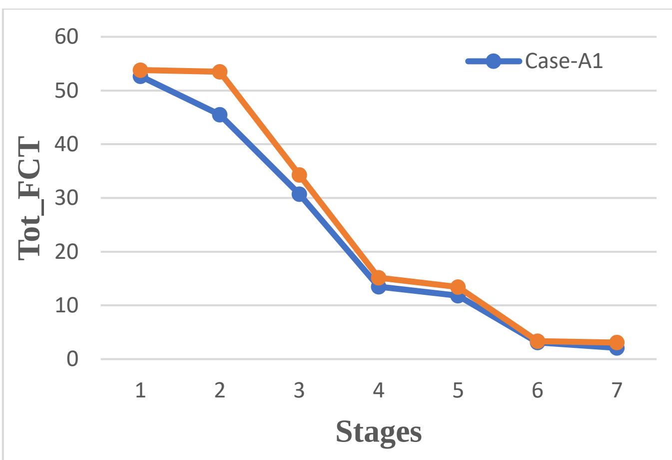

Table 6.26

Description of Stages shown in Figure 6.6(b)

Stage1	Conv.
Stage2	CRRC
Stage3	CAPS2,+Hybrid_algo
Stage4	Stage3+RHs_algo
Stage5	Stage4+FRC1 by DFZD
Stage6	Stage5+FRC2 by DFZD
Stage7	Stage6+info-3

Figure 6.6 (b) Reduction by CAPS-2 in total fault clearing time (*Tot_FCT*) in different stages (as described in Table 6.26).

6.5 CONCLUSION

CAPS-1

The CAPS-1 is an adaptive centralized protection scheme and designed to provide a dedicated protection to both grid-connected and islanded distribution system. It is suitable for the microgrids with DGs possessed with high fault ride through fault capabilities such as synchronous based DGs. In other words, it is suitable for the modern distribution system where the number of DGs can variable only in the normal conditions, while fixed in the faulty condition. It works for the system which is equipped with advanced communication systems and advanced protective devices. Unlike the existing schemes, this scheme is partially dependent on the communication systems. It is capable of providing the optimal relays settings in various types of fault conditions (due to different fault types, impedances, and levels) without being affected by the information loss due to the pre-fault failures of relays and communication links, and by the changes in the system's operating mode (due to grid-connected or islanding operating mode, network re-configuration, and change in number, size, location and types of DGs). The functioning of this scheme is based on the online data of the system due to which it provides the protection which is dedicated to the present operating mode. The response-based protection feature of the scheme makes it adaptive for the known as well as unknown fault situations. The test results validate that the inclusion of the proposed algorithms not only provides the faster clearance of the fault while prevailing the coordination margin between the relays but also enrich the inverse-time protection with intelligent, self-adaptive, robust, and reliable features.

CAPS-2

- The comprehensive adaptive protection scheme-2 (CAPS-2) is an adaptive centralized protection scheme which is designed by using the algorithms and methods (Hybrid_algo, DFZD_algo, RHs_algo, and SCRRC) proposed for different protection stages. This scheme inherits the advantages of all these individual methods.
- Unlike the conventional comprehensive protection approach which is fully dependent on the offline data, the CAPS-2 is partially dependent on the offline data and partially on the online data. This feature makes this scheme a comprehensive scheme in terms of providing coordinated protection in all variable operating modes, and a dedicated scheme in terms of providing relatively more optimal protection to the current operating mode.
- This scheme is suitable for the microgrid with DGs possessed with mixed types of fault ride through fault capabilities (high or low), such as synchronous based DGs and IBDGs.
- This scheme works even if some of the information flow is absent due to FRC.
- Apart from the Hybrid_algo, DFZD_algo, and RHs_algo, the inclusion of the proposed SCRRC relay coordination method intelligently utilizes the information gathered via communication systems to make the protection more effective and faster. The performance of CAPS-2 has been validated by using the test system results.