CHAPTER 2

CONSTRAINTS REDUCTION RELAYS COORDINATION METHOD

2.1 Introduction

A system can appear in various operating modes due to changes in the number of DGs. The number and size of DGs can change during a normal condition to meet the sudden changes in the load demand [99], [100]. For example, internal-combustion engine generators and PV based DGs can be re-connected or disconnected from the grid during peak or low demand respectively. Besides normal conditions, the number of DGs can also change during a faulty condition if some of the DGs possess low fault ride-through capabilities. An inverter-based DG generally has low fault ride-through capability which is typically 1.5-2 times of the rated current [1]. Consequently, these DGs may fail to withstand the high fault currents or low voltages and may get disconnected from the system by its internal protection unit [1] [21]. The variability of operating modes during a normal and/or a faulty condition must be considered while designing a protection scheme otherwise a distribution system will have unsafe and false protection. For this, a protection scheme must be comprehensive so that it can deal with the variability of the operating modes. In [18], [99] comprehensive settings have been determined by satisfying all the constraints related to all the possible operating modes. Where in [99] and [18], variable operating modes due to changing sizes of DGs and changing number of DGs have been considered as a variable entity respectively. This chapter discusses the existing comprehensive method for the coordination of relays, problem formulation, and solution.

2.2 Problem Formulation

In this section, the problem of coordination of relays has been formulated considering the increasing proliferation of DGs with variable connections and sizes. For this, the conventional comprehensive study for coordination of relays has been expanded for DGs considering the variability due to both the number and sizes of DGs. This study shows how the problem of coordination of relays becomes a complex problem with a large set of constraints.

2.2.1 Distribution System with variable number and sizes of DGs

If, maximum $N_{DG_{max}}$ number of DGs of particular sizes can be installed at different candidate locations in the distribution network, and at a time if m number of DGs are considered connected in the distribution system, then because of changes in the number of DGs due to reconnections and disconnections, a system can appear in total $T^{modes}_{(var\_num)}$ different operating modes as shown in Equation (2.1). Where m can vary from minimum m=1 to maximum m= $N_{DG_{max}}$.

$$T^{\text{modes}}_{(\text{var\_num})} = \left[\sum_{m=1}^{N_{DG}^{\max}} C_m^{N_{DG}^{\max}} \right] \tag{2.1}$$

Let's take an example **Example-2.1** where a maximum of 3 DGs (DG-A, DG-B, and DG-C) of particular sizes are connected in a system (i.e. $N_{DG_{max}}$=3) and only number of DGs are variable. Then as per Equation (2.1), total 7 operating modes are possible

TABLE 2.1

OPERATING MODES POSSIBLE WITH THREE DGS WITH FIXED SIZES

No. of DGs	**DG-A**	**DG-B**	**DG-C**
	k_1^{sm}	k_2^{sm}	k_3^{sm}
***m*=1**	**1**	**0**	**0**
	0	**0**	**1**
	0	**1**	**0**
m=2	1	1	0
	1	0	1
	0	1	1
***m*=3**	**1**	**1**	**1**
	Total possible operating modes for NDG_{max} = 3 is 7		

Table 2.2

OPERATING MODES POSSIBLE WITH THREE DGS WITH VARIABLE SIZES

m	**DG1 (n_{s1})**	**DG2 (n_{s2})**	**DG3 (n_{s3})**	**Total Combinations of *sm***	**A***	**T^{modes} for a *m***
m=1	$C_1^{n_{s1}}$	0	0	$C_1^{n_{s1}}$	A1	(A1 +A2 +A3)
	0	$C_1^{n_{s2}}$	0	$C_1^{n_{s2}}$	A2	
	0	0	$C_1^{n_{s3}}$	$C_1^{n_{s3}}$	A3	
m=2	$C_1^{n_{s1}}$	$C_1^{n_{s2}}$	0	$C_1^{n_{s1}} \times C_1^{n_{s2}}$	A4	(A4 +A5 +A6)
	0	$C_1^{n_{s2}}$	$C_1^{n_{s3}}$	$C_1^{n_{s2}} \times C_1^{n_{s3}}$	A5	
	$C_1^{n_{s1}}$	0	$C_1^{n_{s3}}$	$C_1^{n_{s1}} \times C_1^{n_{s3}}$	A6	
m=3	$C_1^{n_{s1}}$	$C_1^{n_{s2}}$	$C_1^{n_{s3}}$	$C_1^{n_{s1}} \times C_1^{n_{s2}} \times C_1^{n_{s3}}$	A7	A7

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

(for *m*=1 to 3) as shown in Table 2.1. The '1' and '0' values of k_i^{sm} denote that the i^{th} DG is in active and inactive state respectively.

Now, suppose, an Example-2.2, where in the Example-2.1, besides variable connections, DG-A, DG-B, and DG-C have variable sizes where they can operate in n_{s1}, n_{s2}, and n_{s3} number of different sizes respectively. Then for a fixed *m* value, the total number of possible operating modes due to changes in both number and sizes of DGs can be determined by the steps as shown in Table 2.2. In Table 2.2, $C_1^{n_{si^{th}}}$ denotes the number of combinations of operating modes possible due to ns_i different sizes of an ith DG. Moreover, a formula, as shown in Equation (2.2), is developed for calculating the total number of operating modes possible due to having the maximum N_{DGmax} proliferation of variable size DGs. The Equation (2.2) can be generalized as Equation (2.3). Where, in Equation (2.3), if k_i^{sm} is 0 (means ith DG is OFF), then U_i^{sm} =1, otherwise $U_i^{sm} = C_1^{n_{si}}$.

$$T^{modes}{}_{(var\_num\_size)} = \sum_{m=1}^{N_{DG}^{\max}} \sum_{sm=1}^{C_m^{N_{DG}^{\max}}} \begin{bmatrix} (k_1^{sm} \times C_1^{ns1})(k_2^{sm} \times C_1^{ns2}).. \\ ...(k_{N_{DG}^{\max th}}^{sm} \times C_1^{nsN_{DG}^{\max th}}) \end{bmatrix} \quad (2.2)$$

$$T^{modes}{}_{(var\_num\_size)} = \sum_{m=1}^{N_{DG}^{\max}} \sum_{sm=1}^{C_m^{N_{DG}^{\max}}} \left[\prod_{i=1}^{N_{DG}^{\max}} U_i^{sm} \right] \quad (2.3)$$

2.2.2 Conventional Comprehensive Relay Coordination (RC) Method

As per the near and far approach [2], a feeder's protective relay must be prepared to protect the feeder from the fault anywhere lie between their maximum near-end and minimum far-end fault current ranges. So, for the distribution system with multi operating modes due to variable entities (number and/or sizes of DGs), the existing conventional comprehensive RC methods [18], [99] use all constraints related to the precalculated maximum near-end and minimum far-end fault currents of a feeder for all possible operating modes.

2.2.2.1 When only the number of DGs is variable

In this case, the selected T^{modes} by the conventional method ($T^{modes}{}_{\_conv}$) will be equal to $T^{modes}{}_{\_var\_num}$ as shown in Equation (2.1). The generalized expression for the total number of required coordination constraints *(*$Tc_{\_constr\_conv}$) and *OF* are developed for the conventional comprehensive settings, which can be shown in Equation (2.4) and Equation (2.6) respectively.

$$Tc_{\_constr} = \left[\sum_{sm=1}^{T^{modes}} \sum_{FZ=1}^{N_{FZ}} \sum_{p=1}^{P_{FZ}^{sm}} B_{\text{p}\_FZ}^{sm} \right]_{nr} + \left[\sum_{sm=1}^{T^{modes}} \sum_{FZ=1}^{N_{FZ}} \sum_{p=1}^{P_{FZ}^{sm}} B_{\text{p}\_FZ}^{sm} \right]_{far} \quad \text{OR} \qquad (2.4)$$

$$Tc_{\_constr} = \left[\sum_{m=1}^{N_{DG\max}} \sum_{sm=1}^{{}^{N_{DG}}C_{m}} \sum_{FZ=1}^{N_{FZ}} \sum_{i=1}^{P_{FZ}^{sm}} B_{i\_FZ}^{sm} \right]_{nr} + \left[\sum_{m=1}^{N_{DG\max}} \sum_{sm=1}^{{}^{N_{DG}}C_{m}} \sum_{FZ=1}^{N_{FZ}} \sum_{i=1}^{P_{FZ}^{sm}} B_{i\_FZ}^{sm} \right]_{far} \qquad (2.5)$$

$$\begin{aligned} OF &= \sum_{sm=1}^{T^{modes}} \sum_{p=1}^{P_{Z}^{sm}} \left[\left(W^{sm} \right)_{nr} + \left(W^{sm} \right)_{far} \right] \\ & \qquad \text{OR} \\ &= \sum_{sm=1}^{T^{modes}} [Tr\_sum] \end{aligned} \qquad (2.6)$$

Where, $$W^{sm} = \left(T_{p\_Z}^{sm} + \sum_{b=1}^{B_{\text{p}\_Z}^{sm}} T_{pb\_Z}^{sm} \right) \qquad (2.7)$$

Thus, for Example-2.1 where N_{DGmax} =3, the T^{modes}*_conv* will be 7 from Equation (2.1). The conv. method uses both maximum and minimum fault currents to obtain *Tc_constr* as shown in Equation (2.4). While, one more set of constraints which includes the constraints related to minimum operating time of relays also takes part while optimizing the relays settings. Thus, total number of constraints i.e. Tot_constr includes both types of above-discussed constraints. Tot_constr depends on the number of coordination relay pairs which further depends on the network configuration.

2.2.2.2 When both number and size of DGs are variable

In this case, the expressions for OF and Tc_constr are the same as shown in Equation (2.6) and Equation (2.4) respectively, except T^{modes}_conv which is equal to $T^{modes}\_var\_num\_size$ as shown in Equation (2.2).

Thus, for Example-2.2, where NDG_{max}=3 and each i^{th} DG have three different sizes i.e. ns_i=3, $C_1^{n_{si}}$ will be 3 as shown in Table 2.1, as a result, T^{modes}_conv will be 63 as explained in Equation (2.8). While Tot_constr will include the constraints related to both maximum and minimum fault currents for all 63 operating modes.

$$\begin{aligned} \mathrm{T}^{\mathrm{modes}}_{conv.}\_Example2.2 &= [(C_1^{ns1} + C_1^{ns2} + C_1^{ns3})_{m=1} + (C_1^{n_{s1}} \times C_1^{n_{s2}} + C_1^{n_{s2}} \times C_1^{n_{s3}} + C_1^{n_{s1}} \times C_1^{n_{s3}})_{m=2} \\ &+ (C_1^{n_{s1}} \times C_1^{n_{s2}} \times C_1^{n_{s3}})_{m=3}\ ] = [(A1 + A2 + A3)_{m=1} + (A4 + A5 + A6)_{m=2} + (A7)_{m=3}] = 63 \end{aligned} \tag{2.8}$$

This section (Section 2.2.2) concludingly reveals mainly two observations: 1. Increment in the number of variable entities significantly increases the T^{modes} and Tot_constr. 2. Aggregation in the proliferation of DGs or increment in the value of NDG_{max} also raises the T^{modes} and Tot_constr, as both are proportional to NDG_{max}. This manifests that a relay coordination problem becomes a highly constrained problem in the presence of variable operating modes, and becomes more complex as the proliferation of DGs in the distribution system goes high.

The next section shows the impact of the conventional RC method on the fault clearing time in the presence of high proliferation of DGs and proposes a solution method, named CRRC.

2.3 Proposed Constraint Reduction Relay Coordination Method (CRRC)

2.3.1 CRRC Method

The relays settings should respond coordinately to both the maximum and the minimum fault currents of a feeder zone in an operating mode. Now, in a multi-operating mode DS, the current number of DGs i.e. the value of m can vary from 1 to the maximum planned N_{DGmax}. The proposed RC method introduces a constraint reduction logic by reducing the T^{mode}, which is as follows. Among the different possible modes, there is only one operating mode with m=N_{DGmax}, in which a feeder relay experiences higher fault current. While, in anyone of the operating modes with m=1, the feeder relay will experience lower fault current compared to the rest of the modes with $m>1$. In other words, the CRRC method works on the logic that a feeder's relay experiences maximum fault current when the number of connected DGs in the system is maximum i.e. when m_{max}= N_{DGmax}, and experiences minimum fault current when the number of DGs is minimum i.e. m_{min}=1.

2.3.1.1 When only the number of DGs is variable: The T^{modes} selected by the CRRC is shown in Equation (2.9), and the expression of the Tot_{constr}_CRRC is shown in Equation (2.10). This shows that compared to the T^{modes}_conv, as shown in Equation (2.1), the CRRC relaxes a lot of constraints corresponding to all the operating modes from m=2 to m=(N_{DGmax} -1) during an optimization process.

$$T_{CRRC}^{modes}(\text{var\_num}) = \left[\sum_{m=1, N_{DG}^{\max}} C_m^{N_{DG}^{\max}} \right] \quad (2.9)$$

$$Tot_{\_constr\_CRRC}(\text{var\_}num) = \left[\sum_{\substack{m=1,\\ N_{DG}^{\max}}} \sum_{sm=1}^{C_m^{N_{DG}^{\max}}} \sum_{i=1}^{P_{FZ}^{sm}} B_{i\_FZ}^{sm} \right]_{nr} + \left[\sum_{\substack{m=1,\\ N_{DG}^{\max}}} \sum_{sm=1}^{C_m^{N_{DG}^{\max}}} \sum_{i=1}^{P_{FZ}^{sm}} B_{i\_FZ}^{sm} \right]_{far} \quad (2.10)$$

For this scenario, the expressions for the $OF_{\_CRRC}$ is the same as the general expression shown in Equation (2.6), except the value of T^{modes} which has been changed now as per the CRRC approach.

The selection of the T_{CRRC}^{modes} and *Tot_constr_CRRC* is explained by using the Example-2.1 of N_{DGmax} =3 as described in the above Section (2.2.1). In this example, the CRRC method will select only 4 operating modes (out of total 7 modes) corresponding to m_{min} =1 and m_{max}=3, as shown in bold font in Table 2.1, and thus will take constraints related to only 4 modes while satisfies the protection coordination in all 7 operating modes.

2.3.1.2 When both the number and size of DGs are variable

In this case also, the maximum and minimum rule, as explained in the above section, is applied on both variable entities: 1. number of DGs and 2. sizes of DGs. Where, for the first variable entity, the CRRC approach first selects the operating modes corresponding to m_{max}= N_{DGmax} and m_{min} =1 from the total T^{modes} given in Equation (2.2). Then, for the second variable entity, it further selects some operating modes from the group of operating modes selected for the first variable entity. Where it selects only

2 operating modes corresponding to the minimum and maximum sizes of a DG. Thus, it uses only 2 sizes from the given n_{si} variable sizes of an i^{th} DG. This can be explained by using Table 2.1, which was prepared for Example-2.1 (this example is described in section 2.2.2). In Table 2.1, for both, m_{min} =1 and m_{max}=3, the values of n_{s1}, n_{s2}, *and* n_{s3} will be equal to 2. Also, as described in Equation (2.11), the CRRC will select only 14 operating modes to determine the comprehensive settings, while the conventional will take 63 operating modes as per the calculation shown in Equation (2.8).

$$\begin{aligned} &\mathrm{T}_{CRRC}^{\mathrm{mod}\,es}\_\mathrm{Example}\,2.2=(C_1^{ns1}+C_1^{ns2}+C_1^{ns3})_{m=1}+(C_1^{n_{s1}}\times C_1^{n_{s2}}\times C_1^{n_{s3}})_{m=3} \\ &=(C_1^2+C_1^2+C_1^2)_{m=1}+(C_1^2\times C_1^2\times C_1^2)_{m=3}=14 \end{aligned} \tag{2.11}$$

Thus, the CRRC approach relaxes a significant number of operating modes. The expressions for $T_{CRRC}^{\mathrm{mod}\,es}$ and OF_CRRC for this scenario where both the number and sizes of DGs are variable are shown in Equation (2.12) and (2.13) respectively. Where in (2.13), the full expression of *Tr_sum* can be seen from Equation (2.6).

$$\begin{aligned} \mathrm{T}_{CRRC\ (\mathrm{var\_num\_size})}^{\mathrm{mod}\,es} &= \left[\sum_{m=1}^{C_1^{N_{DG}^{\max}}}(2)\right]_{m_{\min}}+\left[\prod_{i=1}^{N_{DG}^{\max}}(2)\right]_{m_{\max}} \\ &=\left[2\times N_{DG}^{\max}\right]_{m_{\min}}+\left[2^{N_{DG}^{\max}}\right]_{m_{\max}} \end{aligned} \tag{2.12}$$

The determination of the settings of relays using the proposed CRRC method is shown in the flowchart given in Figure 2.5 on page no. 53.

$$OF_{CRRC(\text{var\_}num\_size)} = \left[\sum_{sm=1}^{2N_{DG}^{\max}} (\text{Tr\_sum}) \right]_{m_{\min}} + \left[\sum_{sm=1}^{2^{N_{DG}^{\max}}} (\text{Tr\_sum}) \right]_{m_{\max}} \quad (2.13)$$

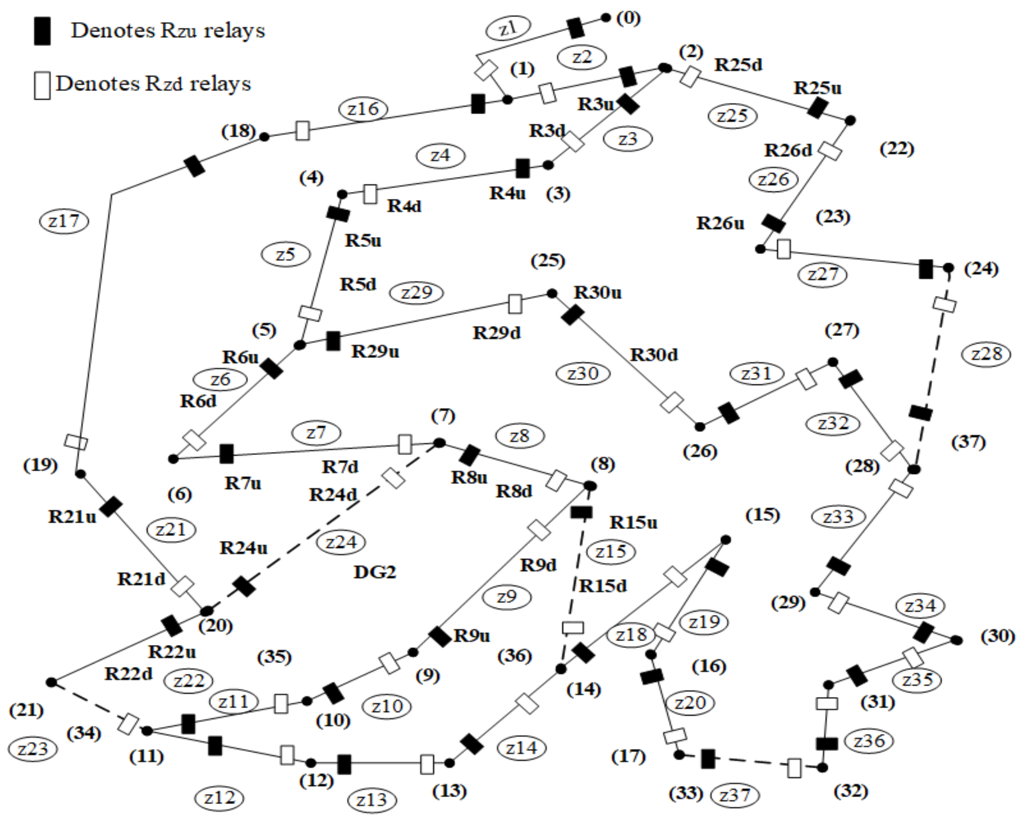

Figure 2.1 Test Distribution system

2.3.2 *Simulation setup, Case Studies, and Results*

2.3.2.1 Simulation Setup

To show the performance of the proposed method for coordination of relays for both radial and meshed configurations, the IEEE 33-bus (also known as IEEE 38-bus) distribution system [4], broadly published in literatures, is employed. The details of the system (shown in Figure 2.1) are given in [101]. The system is a balanced 12.66 KV system with 33 nodes, 32 sectionalizing switches, and 5 ties lines, which 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. To maintain the load-generation balance even after the connection of DGs, each DG of size is connected with their local load of the same size of the DG with unit power factor. The short circuit MVA capacity of each DG is taken as 1.5 times of its rated unit. Each feeder segment is assigned as a z^{th} zone to be protected by the relays located at its both ends. The base MVA is set as 100MVA. In this study, Matlab simpower systems toolbox is used for simulating the fault currents at both ends, and relays are modeled using the current measuring tools and filters in order to measure the power frequency fundamental component of the fault currents. These fault currents with power frequency components are used for computing the settings to restrain the relays from the mal-operation and misdirection of the decision-making due to the presence of harmonics and dc components. For this, it is assumed that the signal processing unit of the advanced numerical relay will deviate all these undesired signals from the polluted current signal, and will give a pure fundamental component of the signal, so that right interpretation of the fault condition and so right tripping decision can be made. The optimization process is done using the linear optimization tool in Matlab. Here, $TMS_{\_min}$=0.01, CTI_{min}=0.3s, T_{i_min}=0.03s, and T_{j_min}=0.33s are assumed. The protection of two feeder zones z31 and z32 of the test network in all possible operating modes are taken for comparison study. The relays settings are computed for both network configurations radial and meshed. Moderate inverse-time characteristic is used for relays with A=19.61, B=0.491 and c=2 [25]. Relays settings are computed for three phase fault currents for both ends of the z^{th}. In both methods, the *PMS* is obtained by multiplying the pre-fault load current with 1.5 multiplier factor [13].

2.3.2.1 Case Studies and Results

A comparative study of the performances of the proposed CRRC and the conventional RC method (as discussed in section 2.2.2) has been carried out for three different cases as explained ahead.

TABLE 2.3
OPERATING MODES POSSIBLE WITH DG-3, 4, AND 5 WITH FIXED SIZES

No. of DGs	Mode (*sm*)	DG3	DG4	DG5
m=1	M1	0	1	0
	M2	1	0	0
	M3	0	0	1
m=2	M4	0	1	1
	M5	1	1	0
	M6	1	0	1
m=3	M7	1	1	1
	Total possible operating modes for NDG_{max} = 3 is 7			

Table 2.4
Relays TMS Obtained for Case-1: With particular size and location of DGs

Relays	Radial Network			Meshed Network		
	Conv.	CRRC (z*32*)	CRRC (z*31*)	Conv.	CRRC (z*32*)	CRRC (z31)
	TMS	*TMS*	*TMS*	*TMS*	*TMS*	*TMS*
R30d	0.6656	0.6656	0.0608	0.6692	0.6692	0.0610
R30u	1.2721	-	0.6681	1.2784	-	0.6706
R31d	0.0607	-	0.0449	0.0609	-	0.0609
R32d	0.4884	0.0481	0.5204	0.6695	0.0610	0.6703
R28d	-	-	-	1.3102	0.6671	-
R33u	1.0089	0.5645	-	1.1677	0.6314	-
R32u		0.0607	-	0.0609	0.0609	-
Tr_sum (s)	43.8827	6.2853	5.7060	62.9285	12.2264	5.9460
Tot_{constr}	132	36	36	196	64	48
Tconv (ms)	36.283	17.142	17.981	51.054	22.222	23.052

Case-1: *Only number of DGs is variable (With particular size and location of DGs)*

To explain this case, in the test system shown in Figure 2.1, three DGs, named DG-3, DG-4, and DG-5 are connected at buses 29, 6 and 24 respectively, where the size of each DG is taken as 3 MVA. With 3 DGs, the test Distribution system can operate in 7

TABLE 2.5

COMPARATIVE PERFORMANCE OF THE CRRC METHOD FOR FAULTED z32 ZONE IN DIFFERENT OPERATING MODES (CASE-1)

Modes	P/B	Radial Network				Meshed Network			
		Near 'u'-end fault		Far 'u -end fault		Near 'u -end fault		Far 'u -end fault	
		Conv.	CRRC	Conv.	CRRC	Conv.	CRRC	Conv.	CRRC
		To_nr (s)	To_nr (s)	To_fr (s)	To_fr (s)	To_nr (s)	To_nr (s)	To_fr (s)	To_fr (s)
M1	P_u	0.0333	0.0333	0.0352	0.0352	0.0323	0.0323	0.0344	0.0344
	B_u	0.3690	0.3690	0.3916	0.3916	0.3585	0.3585	0.3852	0.3852
	P_d	NO	NO	NO	NO	0.3619	0.0319	0.3455	0.0310
	B_d	NO	NO	NO	NO	0.6619	0.3338	0.6536	0.3310
	B_d	NO	NO	NO	NO	2.5251	0.9871	1.2303	0.5422
Tr_sum in M1		0.4023	0.4023	0.4268	0.4268	3.9397	1.7436	2.649	1.3238
M2	P_u	0.0311	0.0311	0.0317	0.0317	0.0302	0.0302	0.0305	0.0305
	B_u	0.3388	0.3388	0.3449	0.3449	0.3317	0.3317	0.3345	0.3345
	P_d	1.1433	0.0805	1.0761	0.0764	0.3342	0.0303	0.3314	0.0301
	B_d	3.0217	1.1715	2.8331	1.1073	0.6913	0.3437	0.6691	0.3362
	B_d	NO	NO	NO	NO	2.0562	0.8279	1.1413	0.5111
Tr_sum in M2		4.5349	1.6219	4.2858	1.5603	3.4436	1.5638	2.5068	1.2424
M3	P_u	0.0333	0.0333	0.0351	0.0351	0.0307	0.0307	0.0314	0.0314
	B_u	0.3689	0.3689	0.3906	0.3906	0.3363	0.3363	0.3431	0.3431
	P_d	NO	NO	NO	NO	0.3422	0.0308	0.3354	0.0304
	B_d	NO	NO	NO	NO	0.9522	0.4310	0.8101	0.3835
	B_d	NO	NO	NO	NO	5.1119	1.8279	1.8936	0.7723
Tr_sum in M3		0.4022	0.4022	0.4257	0.4257	6.7733	2.6567	3.4136	1.5607
M4	P_u	0.0333	0.0333	0.0353	0.0353	0.0301	0.0301	0.0303	0.0303
	B_u	0.3696	0.3696	0.3926	0.3926	0.3318	0.3318	0.3346	0.3346
	P_d	NO	NO	NO	NO	0.3311	0.0301	0.3299	0.0300
	B_d	NO	NO	NO	NO	0.7570	0.3657	0.7047	0.3482
	B_d	NO	NO	NO	NO	3.9899	1.4707	1.6224	0.6787
Tr_sum in M4		0.4029	0.4029	0.4279	0.4279	5.4399	2.2284	3.0219	1.4218
M5	P_u	0.0300	0.0300	0.0302	0.0302	0.0303	0.0303	0.0306	0.0306
	B_u	0.3301	0.3301	0.3318	0.3318	0.3339	0.3339	0.3388	0.3388
	P_d	0.3584	0.0313	0.3503	0.0308	0.3323	0.0302	0.3305	0.0301
	B_d	0.6886	0.3483	0.6757	0.3436	0.7013	0.3470	0.6744	0.3380
	B_d	NO	NO	NO	NO	1.0475	0.4781	0.7628	0.3775
Tr_sum in M5		1.4071	0.7397	1.388	0.7364	2.4453	1.2195	2.1371	1.115
M6	P_u	0.0307	0.0307	0.0311	0.0311	0.0309	0.0309	0.0318	0.0318
	B_u	0.3348	0.3348	0.3390	0.3390	0.3382	0.3382	0.3469	0.3469
	P_d	0.8573	0.0629	0.8127	0.0601	0.3440	0.0309	0.3361	0.0304
	B_d	2.2853	0.9186	2.1565	0.8737	0.6979	0.3459	0.6719	0.3372
	B_d	NO	NO	NO	NO	0.7454	0.3713	0.6386	0.3333
Tr_sum in M6		3.5081	1.347	3.3393	1.3039	2.1564	1.1172	2.0253	1.0796
M7	P_u	0.0300	0.0300	0.0301	0.0301	0.0300	0.0300	0.0301	0.0301
	B_u	0.3300	0.3300	0.3317	0.3317	0.3300	0.3300	0.3313	0.3313
	P_d	0.3461	0.0305	0.3387	0.0300	0.3300	0.0300	0.3294	0.0300
	B_d	0.6491	0.3338	0.6387	0.3300	0.6574	0.3323	0.6507	0.3300
	B_d	NO	NO	NO	NO	0.7192	0.3620	0.6294	0.3300
Tr_sum in M7		1.3552	0.7243	1.3392	0.7218	2.0666	1.0843	1.9709	1.0514
Tr_sum _allM		12.0130	5.6405	11.6326	5.6028	26.2649	11.6134	17.7248	8.7947

different operating modes (M1 to M7) as shown in Table 2.3**.** M1, M2, M3 appears when *m*=1, M7 appears when $m = N_{DGmax}$, and the intermediate M4, M5, M6 modes happen when $1 < m < N_{DGmax}$. The results are obtained for two zones, z32 and z31. By using all 7 possible operating modes' constraints, the CRRC determines one set of relays settings for both zones. On the other side, the CRRC uses only 4 operating modes' constraints and determines individual *TMS* settings for z32 and z31 zones. This is shown in Table 2.4. This table also shows the additional performance results including objective function values, constraints used, and optimization convergence time. The fault clearing time in different op_ modes have been obtained for both near-end and far-end fault currents of the faulted feeder zone, where the results for faulted z32 and z31 zones are shown in Table 2.5 and Table 2.6 respectively. The results of these tables show that the settings calculated using the proposed method not only satisfies the constraints associated with the minimum and maximum modes (M1, M2, M3, and M7) which are used but also satisfies the constraints associated with the intermediate modes (M4, M5 and M6) which have not been used while optimizing the

TABLE 2.6
COMPARATIVE PERFORMANCE OF THE CRRC METHOD FOR FAULTED Z-31 ZONE IN DIFFERENT OPERATING MODES (CASE-1) (IN SEC)

modes with DGs	Radial Network				Meshed Network			
	Near 'u'-end fault		Far 'u -end fault		Near 'u -end fault		Far 'u -end fault	
	Conv.	CRRC	Conv.	CRRC	Conv.	CRRC	Conv.	CRRC
	Tr_sum_nr	*Tr_sum_nr*	*Tr_sum_far*	*Tr_sum_far*	*Tr_sum_nr*	*Tr_sum_nr*	*Tr_sum_far*	*Tr_sum_far*
M1	1.0125	0.3815	1.0816	0.4081	1.4379	0.7903	1.4461	0.7792
M2	2.3389	1.3685	2.2499	1.3069	1.3323	0.729	1.3296	0.7255
M3	1.0147	0.3823	1.0819	0.4082	1.3576	0.7443	1.3499	0.7354
M4	1.0134	0.3818	1.0841	0.409	1.3254	0.7243	1.3289	0.7245
M5	1.3756	0.738	1.3685	0.7317	1.3315	0.7274	1.3378	0.7285
M6	1.9793	1.1384	1.9212	1.0974	1.3641	0.748	1.357	0.7385
M7	1.3605	0.7277	1.3548	0.7223	1.3202	0.7213	1.3215	0.7214
Tr_sum_allM	10.0950	5.1182	10.1421	5.0835	9.4689	5.1843	9.4708	5.1527

TABLE 2.7
OVERALL COMPARISON RESULTS FOR CASE-1

For both z32 and z31	Radial Network		Meshed Network	
	Conv.	CRRC	Conv.	CRRC
*Total Sum.*of OT (s)	43.8827	21.4449	62.9285	30.7451
Tot_constr	132	72	196	112
Total *Tconv* (ms)	36.283	35.123	51.054	45.274

TABLE 2.8
PERFORMANCE OF THE CRRC IN CASE-2

Faulted FZs	Relays	**P/B**	M4		M5		M6	
			Tr_nr (s)	*Tr_far* (s)	*Tr_nr* (s)	*Tr_far* (s)	*Tr_nr* (s)	*Tr_far* (s)
z5	R5u	P_u	0.0302	0.0309	0.0302	0.0310	0.0300	0.0303
	R4u	B1_u	0.3319	0.3389	0.3320	0.3395	0.3299	0.3329
	R5d	P_d	0.0323	0.0307	0.0323	0.0307	0.0304	0.0299
	R6d	B1_d	0.3374	0.3348	0.3341	0.3331	0.3701	0.3518
	R29u	B1_d	0.6573	0.3984	0.6097	0.3825	0.4623	0.3342
z29	R29u	P_u	0.0385	0.0365	0.0370	0.0352	0.0310	0.0303
	R5u	B1_u	0.4387	0.4143	0.4215	0.4003	0.3390	0.3329
	R6d	B1_u	0.0307	0.0309	0.0305	0.0307	0.0300	0.0301
	R29d	P_d	0.3369	0.3396	0.3375	0.3403	0.3299	0.3308
	R30d	B1_d	0.3332	0.3340	0.3315	0.3318	0.3502	0.3564
z6	R6u	P_u	0.0301	0.0302	0.0300	0.0301	0.0302	0.0303
	R5u	B1_u	0.3382	0.3450	0.3388	0.3460	0.3301	0.3320
	R29d	B1_u	0.4280	0.5741	0.4052	0.5303	0.3359	0.3942
	R6d	P_d	0.0302	0.0302	0.0301	0.0301	0.0318	0.0312
	R7d	B1_d	0.3326	0.3318	0.3310	0.3307	0.3495	0.3437
z7	R7u	P_u	0.0301	0.0301	0.0300	0.0300	0.0306	0.0311
	R6u	B1_u	0.3316	0.3333	0.3309	0.3322	0.3330	0.3355
	R7d	P_d	0.0300	0.0300	0.0300	0.0300	0.0320	0.0312
	R8d	B1_d	0.3266	0.3220	0.3331	0.3254	0.4492	0.3891

settings. Results also show that all the relays operating times and CTI between each P and B relay pair satisfy specified limits for the operating times which is 0.03s for a P and 0.33s for a B with specified minimum *CTI* which is 0.3s. The comparative analysis has been discussed in detail in later sub-section. The summary of the combined comparative performance for both zones is shown in Table 2.7.

***Case-2*: Only number of DGs is variable** *(*With both new location and sizes of DGs)

To further test the performance of the CRRC method, a case has been taken with new locations and sizes of DGs (DG3, DG4, and DG5) which are (26, 9, and 14) and (2MVA, 5MVA, and 3 MVA) respectively, while the operating modes (M1 to M7) are the same as given in Table 2.4. This case has been investigated for four different zones, z5, z29, z6, and z7, in the meshed configuration of the distribution system. The operating time of the relays for all the intermediate operating modes (M4, M5, and M6) are shown in Table 2.8, which further reveals that the CRRC method satisfies the coordination constraints even for the operating modes which are not taken while optimzing the settings. The overall comparison has been shown in Table 2.10.

Case-3*: With both variable number and size of DGs*

The proposed method computes the optimal settings for relays which are not only adaptive to the variable numbers of DGs but also simultaneously adaptive to the variable size of the DGs. To testify it, case-3 is conducted in which two DGs i.e. DG3 and DG4 are connected to the meshed test system at the bus-26 and bus-9 respectively, where DG3 is set with a fixed size i.e. 2 MVA, while DG4 is set with a variable size whose size can change from 3 MVA to 4MVA and 4MVA to maximum 5 MVA in future. Thus, as explained in Section 2.2.1, these two DGs can be appeared in 7 different operating modes, which are (2MVA, 0), (2MVA, 3MVA), (2MVA, 4MVA), (2MVA, 5MVA), (0, 3MVA), (0, 4MVA), (0, 5MVA). The proposed method selects only 5

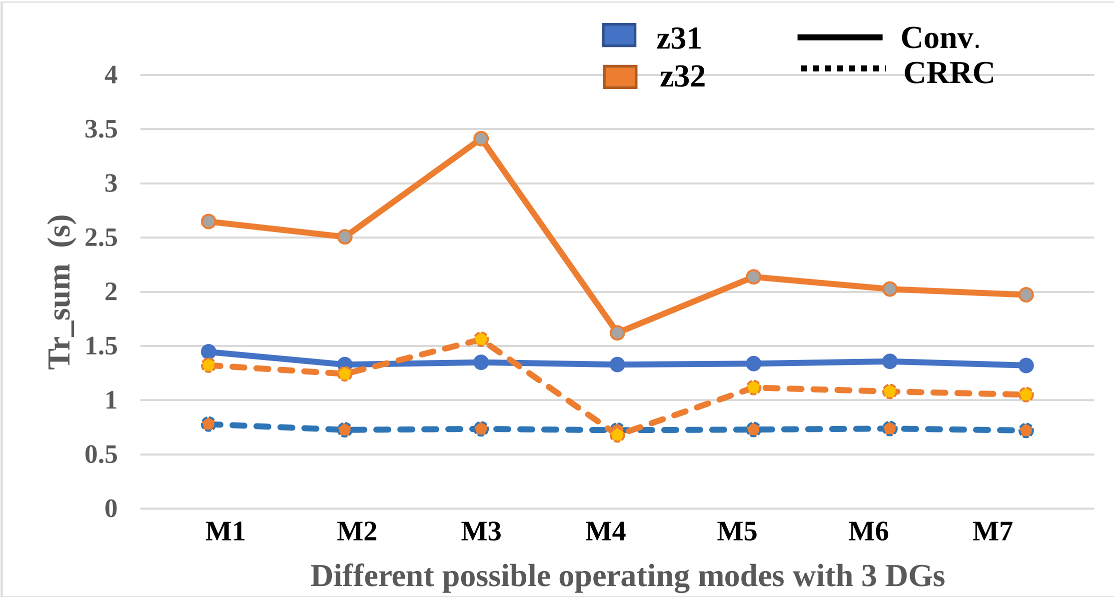

Figure (2.2) Comparison between *Tr_sum* obtained by the proposed CRRC and the Conv. for far-end faults for all 7 possible operating modes in Case-1 in Meshed configuration

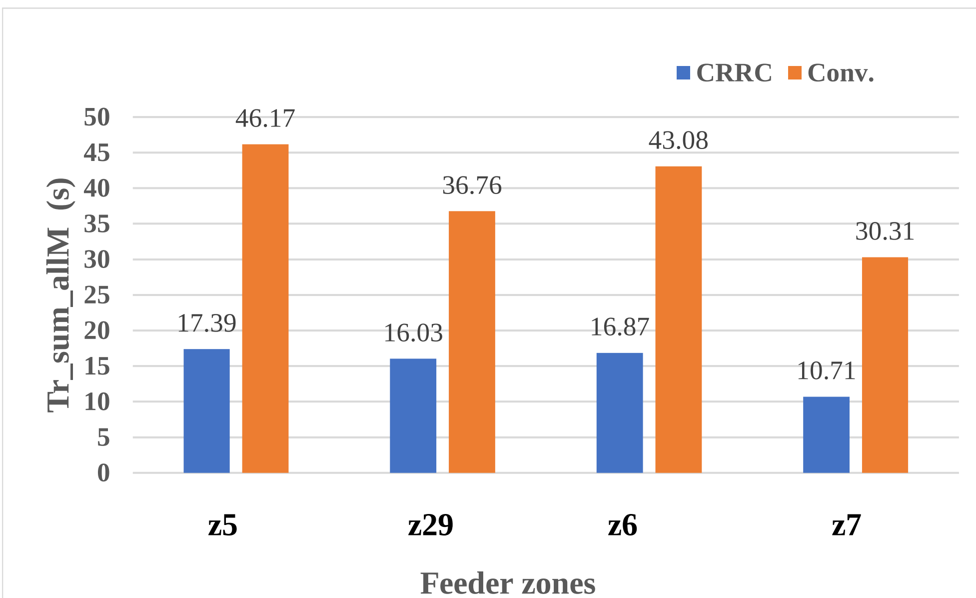

Figure (2.3) Comparison between the Tr_sum_allM obtained by the proposed CRRC and the Conv. in Case-2 in Meshed Configuration

modes out of the total 7 modes as described as follows. Where, it selects modes for *m*=1 with minimum and maximum sizes of DGs, which are (2MVA,0), (0, 3MVA)

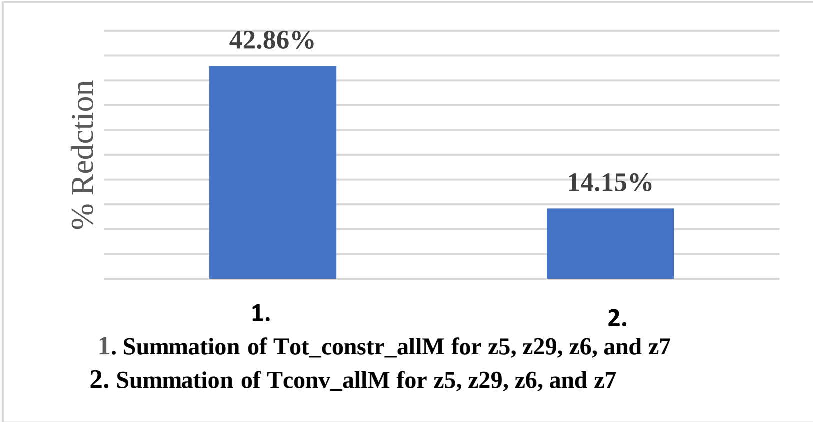

Figure 2.4 Overall Percentage Reduction in the constraints and convergence time with respect to the Conv in Case-2

TABLE 2.9
OBTAINED RELAYS OPERATING TIMES USING CRRC METHOD FOR INTERMEDIATE OPERATING MODES WITH VARIABLE DG-SIZE (CASE-3)

Fault zone Z_5					
		M_interm1 (2, 4)		M_interm2 (0, 4)	
Relays	TMS	Tr_nr (s)	Tr_fr (s)	Tr_nr (s)	Tr_fr (s)
R29d	0.056	0.0358	0.0342	0.0311	0.0304
R30d	0.6259	0.4068	0.3885	0.3398	0.3335
R29u	0.0606	0.0304	0.0306	0.0300	0.0301
R5u	0.6643	0.3377	0.3405	0.3300	0.3310
R6d	0.6711	0.3296	0.3296	0.3511	0.3576
Tr_sum = 11.4271 s, *Tot_constr* = 80					
Fault zone Z_6					
		M_interm1 (2, 4)		M_interm2 (0, 4)	
Relays	TMS	Tr_nr (s)	Tr_fr (s)	Tr_nr (s)	Tr_fr (s)
R6d	0.061	0.0300	0.0300	0.0313	0.0313
R7d	0.6707	0.3303	0.3303	0.3539	0.3539
R6u	0.061	0.0300	0.0300	0.0303	0.0303
R5u	0.6653	0.3449	0.3449	0.3326	0.3326
R29d	0.5553	0.5136	0.5136	0.3765	0.3765
Tr_sum = 12.0569 s, *Tot_constr* = 80					

and (0, 5MVA) here. At the same time, it also selects modes for m= NDG_{max} (as the NDG_{max} =2) with minimum and maximum sizes of DGs, which are (2MVA, 3MVA) and (2MVA, 5MVA) here. The obtained results in Table 2.9 assure that the calculated relays-settings not only satisfy these 5 modes but also satisfy those intermediate modes that associated constraints are get relaxed during the proposed coordination optimization process. Here, the intermediate modes are (2MVA, 4MVA) and (0, 4MVA), and have been denoted as M_interm1 and M_interm2 respectively in the result Table 2.9.

TABLE 2.10
OVERALL COMPARISON OF TABLE 2.8 RESULTS FOR SCENARIO-2

	CRRC	Conv.
	**Tr_sum_allM* (nr+fr)	*Tr_sum_allM* (nr+fr)
z5	46.1671	17.3954
z29	36.7664	16.0296
z6	43.0793	16.8742
z7	30.3100	10.7096
Tr_sum_allM for all zones	156.3229	61.0088 (60.9% reduction)
Tot_constr_all M	420	240
Total *Tconv* (ms)	102.789	88.245

* *Tr_sum_allM* of all 7 operating modes including both near and far end faults (in sec)

2.3.3 Comparative Performance Evaluation and Advantages

A. Influence on the Relays Operating Times, Coordination, and speed of the protection

The relays operating times obtained using the CRRC not only satisfy the specified minimum limits for relays operating time and *CTI* in all operating modes but also provides overall faster fault clearing time compared to the conventional method. For example: in Table 2.7 and Table 2.10, in Case-1 and 2, CRRC yields relays operating times approximately 50% faster than the existing conventional method. This advantage of the proposed CRRC is also explained in the figures Figure 2.2 and Figure 2.3.

B. *Influence on the number of constraints and convergence speed*

The CRRC method relaxes a major number of constraints. A detail explanation is given below:

i) It relaxes the constraints for all *sm* operating modes corresponding to $1 < m < N_{DGmax}$, and uses the constraints for *sm* corresponding to only the minimum and maximum proliferation of DGs i.e. only for m=1 and $m=N_{DGmax}$. On the contrary, existing methods use all the constraints corresponding to all the values of *m* and *sm.* This is explained by using Table 2.11, which shows T^{modes} selected by both conventional and proposed CRRC methods in the presence of variable size DGs. It can be observed that as the proliferation of variable DGs increases, CRRC reduces significantly number of T^{modes} compared to the conventional. This manifests the imporatnce of the CRRC approach in the protection of the system with high proliferation of DGs.

TABLE 2.11
IMPACT OF INCREASING PROLIFERATION OF DGS ON TOTAL NUMBER OF OPERATING MODES

Max. number of DGs	$N_{DG_{\max}} = 2$	$N_{DG_{\max}} = 3$	$N_{DG_{\max}} = 4$
Name of DG (ns_i)	DG-1 (1), DG-2 (3)	DG-1 (1), DG-2 (3), DG-3 (3)	DG-1 (1), DG-2 (3), DG-3 (3), DG-4 (3)
$T_{conv.}^{modes}$	7	31	127
T_{CRRC}^{modes}	5	8	15

ii) It relaxes constraints related to the (N_{FZ} -1) feeder zones and takes only the constraints associated to the faulted feeder zone. While the conventional method takes the constraints for all N_{FZ} feeder zones. This can also be explained mathematically by comparing Equation (2.5) and Equation (2.10) which shows that the CRRC method removes the second summation and the values of *m* from 2 to (N_{DG}-1) from the last summation in Equation (2.5).

The influence of the CRRC on the number of constraints can also be observed by the test results shown in Tables 2.7, Table 2.10, and Figure 2.4, which show approximately 43% reduction in the number of constraints. In addition, these results also show that the CRRC provides comparatively faster convergence of the optimization problem.

C. Works for different sizes and location of DGs

The fault current in a feeder changes with either the distance of a DG from that feeder or the size of the DG or with both. Therefore, a change in the size and location of DGs demands a relook into the settings of relays. It is observed from the results of case-2 that the CRRC method is applicable for different types of entries of locations and variable sizes of DGs. Thus, this method is capable of determining the relays settings considering future increments in the size of DGs, as shown by Table-J.

2.4 Conclusion

This chapter proposes a novel constraints reduction based optimal relay coordination method for the distribution system with high penetration of the DGs, where the number of DGs can change during normal and faulty conditions. This method yields the comprehensive settings for relays while satisfies the relay coordination in all possible operating modes by satisfying only the minimum and maximum criterias for the variable entities which are here, number and sizes of DGs. With this method, there is no need of re-optimization for new

TMS if mode gets changed. The effectiveness of the proposed method has been shown by conducting a comparative study with the conventional method. The comparative results show that the proposed CRRC method releases approximately 43% burden of constraints from the coordination optimization process, and resulting provide relatively more optimal *TMS* settings which yield faster operating times of relays, faster fault clearance of the fault, and smaller optimization convergence time. The proposed method is also applicable for future situations when besides the number of DGs, size of DGs becomes variable. The performance of the proposed method in variable operating modes has been verified for both radial and meshed network configurations of the test system with changing locations and sizes of DGs. The proposed constraints reduction approach of protection using maximum and minimum conditions can be utilized by the other protection schemes in future researches.

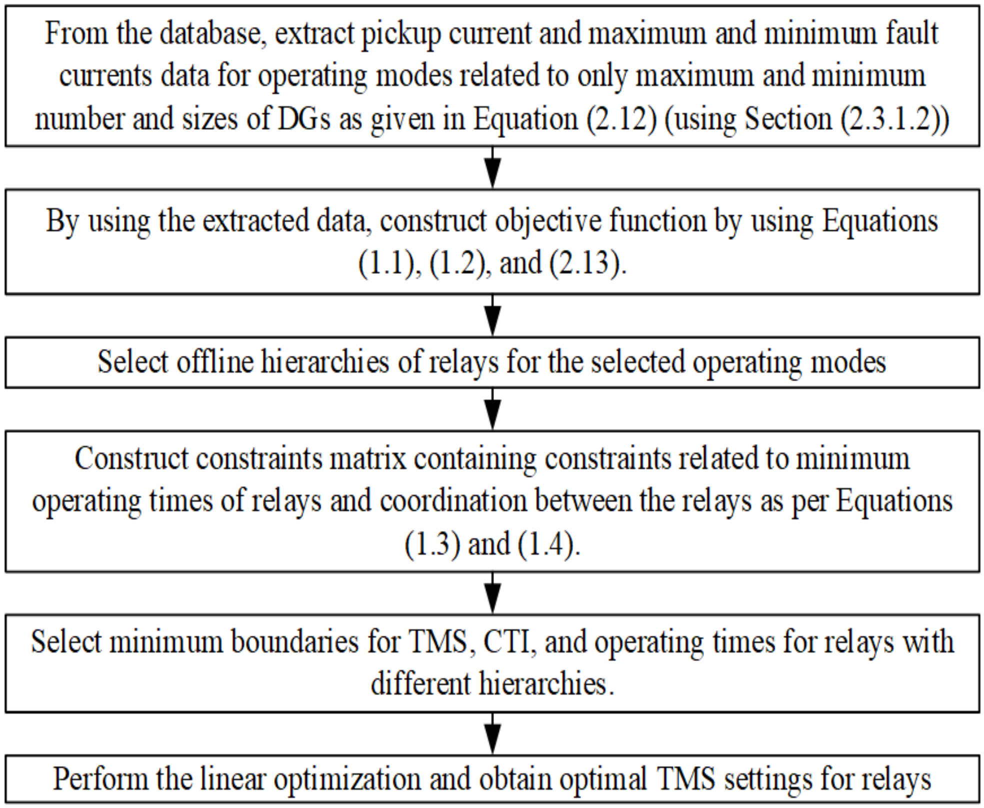

Figure 2.5 Flowchart for determining the settings for relays using the proposed CRRC method