Overcurrent Relay Coordination in a Grid-Connected Microgrid System

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***Abstract*—Overcurrent faults are predominant in microgrid systems and high currents may cause damage to devices. Therefore, protection system for microgrids is required to isolate the devices from faults in the system. It is also critical to provide necessary primary and backup protection systems with proper time grading to isolate such faults. Overcurrent (OC) Relays are frequently used in microgrids and it is necessary to optimize the time multiplier setting (TMS) of relays, which in turn minimizes the time of operation of the relays. In this paper, Dual Simplex and Revised Simplex optimization techniques are used to optimize the TMS value of relays and thereby to achieve quick fault clearance. The optimized TMS values of relays are obtained using Dual Simplex and Revised Simplex methods.**

***Index Terms*—Dual Simplex Method; Revised Simplex Method; Microgrid Protection; Operating Time; Overcurrent Relay Coordination; Time Multiplier Settings;**

I. INTRODUCTION

As the energy demand increases, the need for a reliable, efficient and lasting power supply system also increases. This encouraged the introduction of the concept of a micro-grid. Micro-grid is a small-scale interconnected energy system consisting of intelligently controlled loads and distributed energy resources, which is able to operate in both, grid connected and islanded mode[1]. It has various advantages such as increase in security, reduction in cost and generation of revenue at the time of peak demand. It can also be integrated with the renewable forms of energy supply[2]. There are various challenges in implementing a micro-grid in the two modes. Stabilizing energy, power management and protection system are some of the major issues faced in the operation of a micro-grid system[3]. Protection system should consist of dynamically coordinated arrangement of relays, which would isolate the fault from the micro-grid as fast as possible to protect it. Various methods are used for treating the issue of relay coordination[4]. One such method is optimizing the problem while considering it as a linear programming problem (LPP) and solving it using a specific method along with its variants. The two conventional methods, which may be employed are: a) dual simplex method and b) revised simplex method[5-7]. This paper analyzes the overcurrent relay coordination problem in a microgrid system using dual simplex and revised simplex method. It also compares the two methods in terms of optimization efficiency.

II. OVERCURRENT RELAY COORDINATION IN MICROGRID

The microgrid test system is shown in Figure 1. Let us consider segment B for our analysis. Fault at any point of the network must be isolated quickly to save the healthy portion of the network from the faulted network. Thus, an effective overcurrent relay coordination scheme should be employed with quick fault clearance capability.

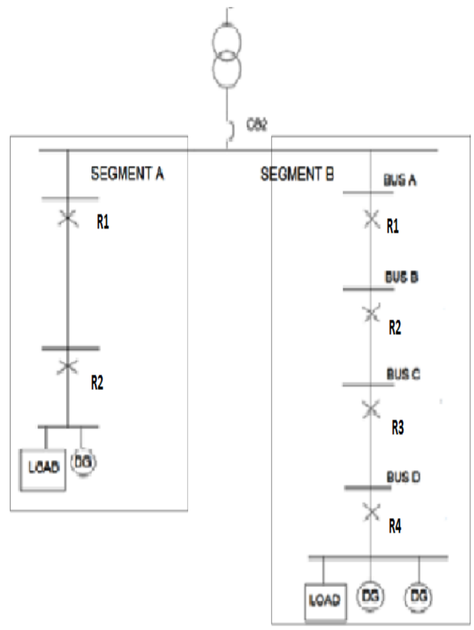

Figure 1: Microgrid test system

III. FORMATION OF LINEAR PROGRAMMING PROBLEM

In a faulted system, the relay closest to the fault acts as the primary relay and the remaining upstream relays act as the back-up relays. Each consecutive pair of the relays in the system acts as a primary-back-up relay pair, with the relay nearer to the fault as the primary relay and the consecutive upstream relay as the back-up relay. In segment B, if a fault occurs near the load, then relay R_4 is the first one to operate followed by relays R_3, R_2 and R_1. If relay R_4 fails to clear the fault within the time of operation, relay R_3 should act as backup relay. In a similar way, relay R_2 acts as a backup relay for relay R_3, whereas relay R_1 acts as a backup relay for R_2. The segment B can hence be treated as a radial network on which the conventional overcurrent relay coordination can be employed. Let the operating time of relays R_1, R_2, R_3 and R_4 be TR_1, TR_2, TR_3 and TR_4 respectively. The operating time of each relay is also compared as follows $TR_1>TR_2>TR_3>TR_4$.

The PSM values computed in Table 2 are used in following computations:

$$t_{op} = \sum C_n \,(TMS_n) \qquad (1)$$

where TMS is the Time Multiplier Settings.

$$C_n = \frac{\lambda}{((PSM_n)^{\chi}) - 1} \qquad (2)$$

For normal IDMT (Inverse Definite Minimum Time) relay, ɣ is 0.02 and λ is 0.14. The minimum operating time for each relay is considered as 0.2 s and the CTI is taken as 0.3s. Value of C_n is computed.

The Plug Setting Multiplier (PSM) is calculated as:

PSM=(Fault current in relay coil)/[(Rated CT secondary current)*(Current setting)] (3)

A. Objective function

The objective function can be formulated as the sum of the operating time of each relay in the system.

$$\text{Minimize } Z = TR_1 + TR_2 + TR_3 + \ldots TR_n \qquad (4)$$

In this case, Minimize Z=$TR_1+TR_2+TR_3+TR_4 = T_{op}$. Let T_{op} be the sum of the time of operation of each relay.

B. Constraint condition due to the coordination

Time Interval (CTI): $T_b - T_p \geq CTI$ where, T_b is the operating time of the back-up relay, T_p is the operating time of the primary relay and CTI is the coordination time interval.

C. Constraint Condition Due to The Minimum Time of Operation of A Relay

There is a minimum time of operation associated with each relay, which will affect the total time taken to protect the system against the fault. This also creates a constraint to the relay coordination that needs to be performed.

IV. Optimisation Methods

The time multiplier settings of a relay in a microgrid can be optimized using various algorithms. This further optimizes the time of operation of the relay and this aids in clearing the fault faster. In this paper, Dual simplex algorithm and Revised Simplex algorithm have been used for optimizing TMS values of relays in the microgrid (Figure 1).

A. Dual simplex algorithm

The steps to be followed are:

1. Form a matrix containing the lpp and constraints according to the given variables (x1, x2..).
2. Take the transpose of the matrix and formulate the lpp as a function of new variables (y1, y2..).The number of constraints has thus, been reduced.
3. Now add slack variables and solve the problem using simplex method for which we tabulate the new variables (y1, y2..), their coefficients, constraints and the lpp.
4. Perform iterations until the solution of the lpp has been obtained.
5. Replace it in the lpp to obtain the value of the time of operation of the relay.

B. Revised simplex algorithm

1. In the minimization of the lpp, we first frame the dual of the given problem according to the steps mentioned above.
2. Slack variables are added to the constraints.
3. The tabulation is done accordingly and the values of pivot column (P), π matrix are calculated.
4. Iterations are performed till the solution of the lpp is obtained.
5. Replace the values of the variables in the lpp to find the time of operation of the relay.

V. Application of Algorithms

Consider Figure 1 for analysis, whose fault current and CT ratios are taken as shown in Table 1. The PSM and Cn of these relays are shown in Table 2 and Table 3 respectively.

Table 1
Fault current and CT ratio for the relays

Relay	Fault current(kA)	CT Ratio
R1	2.808	600:5
R2	1.404	300:5
R3	1.404	300:5
R4	5.616	1200:5

Table 2
PSM for the relays

Bus	R1	R2	R3	R4
A	23.4	-	-	-
B	11.7	23.4	-	-
C	11.7	23.4	23.4	-
D	46.8	93.6	93.6	23.4

Table 3
Calculation of Cn for the relays

Fault Position	R1	R2	R3	R4
Just beyond Bus A	2.15	-	-	-
Just beyond bus B	2.77	2.15	-	-
Just beyond bus C	2.77	2.15	2.15	-
Just beyond bus D	1.75	1.47	1.47	2.15

Let us consider x1, x2, x3 and x4 be the TMS of relays R1, R2, R3 and R4. Thus, the problem when the default is just beyond bus D can be stated as:

In segment B:
Minimize: Z = 2.15 x1 + 2.15 x2 + 2.15 x3 + 2.15 x4
Subject to the constraints:
2.15 x1 ≥ 0.2, 2.15 x2 ≥0.2,
2.15 x3 ≥ 0.2, 2.15 x4 ≥ 0.2,
1.75 x1 – 1.47 x2 ≥ 0.3,
1.47 x2 - 1.47 x3 ≥ 0.3,
1.47 x3 – 2.15 x4 ≥ 0.3

In segment A:
Minimize: Z=2.15x1 +2.15x2
Subject to the constraints:
2.77x1 – 2.15x2 ≥0.3
2.15 x1 ≥ 0.2
2.15 x2 ≥ 0.2

Let the dual simplex method and the revised simplex method be employed on the above test system. The dual simplex method uses the theory of duality. This method is advantageous to use when the number of constraints is more than the number of variables.

A. Dual Simplex Employed on Segment A

Step 1: Tabulate the problem in matrix form as shown in Table 4.

Step 2: Take the transpose of the above matrix and rewrite the matrix in terms of 'y' variables as shown in Table 5.
The new LPP thus becomes:
Maximize Z=0.2y1+ 0.2y2+ 0.3y3
Subject to the constraints:
2.15y1 + 2.77y3 <= 2.15
2.15y2 – 2.15y3 <= 2.15

Step 3: Adding slack variables:
LPP:
Z=0.2y1+ 0.2y2+ 0.3y3+0S1+ 0S2
Constraints:
2.15y1 + 2.77y3 +S1= 2.15
2.15y2 – 2.15y3 +S2= 2.15

Step 4: The dual of the above problem has been framed.

Table 4
Matrix for Segment A

2.15	0.00	0.20
0.00	2.15	0.20
2.77	-2.15	0.30
2.15	2.15	-

Table 5
Transpose of Matrix

2.50	0.00	2.77	2.15
0.00	2.15	-2.15	2.15
0.20	0.20	0.30	-

Further, we have to solve the problem by Simplex method. CB coefficients of surplus variables in the objective function, B column contains the surplus variables, Cj row has the coefficients of surplus variables in the objective function and XB column has the RHS of the constraints. Zj is the sum of the product of each column element of the variables with its respective CB. The iterations of dual simplex for Segment A are as shown in Table 6, Table 7 and Table 8.

Table 6
Iteration 1 using Dual Simplex Method for Segment A

		C_j	0.2	0.2	0.3	0	0	Sol^n	Ratio
Fixed ratio	C_b	BV	Y1	Y2	Y3	S1	S2		
	0	S1	2.15	0	2.77	1	0	2.15	2.15/2.77
	0	S2	0	1	-1	0	1	1	-1
		Zj	0	0	0	0	0		
		C_j-Z_j	0.2	0.2	**0.3**	0	0		

Table 7
Iteration 2 using Dual Simplex Method for segment A

		C_j	0.2	0.2	0.3	0	0	Sol^n	Ratio
Fixed ratio	C_b	BV	Y1	Y2	Y3	S1	S2		
0	0.3	Y3	0.77	0	1	0.3	0	0.77	-
	0	S2	0.77	0	1	0.3	1	1.77	1.77
		Zj	0.231	0	0.3	0.108	0		
		C_j-Z_j	-0.3	**0.2**	0	-0.1	0		

Table 8
Iteration 3 using Dual Simplex Method for Segment A

		Cj	0.2	0.2	0.3	0	0	Sol^n	Ratio
Fixed ratio	Cb	BV	Y1	Y2	Y3	S1	S2		
	0.3	**Y3**	0.77	0	1	0.36	0	**0.78**	
	0.2	**Y2**	0.77	1	0	0.36	1	**1.78**	
		Zj	0.385	0.2	0.3	0.18	0.2		
		Cj-Zj	-0.185	0	0	-0.18	0		

Consequently, the values of Y3 and Y2 turn out to be 0.77 and 1.77 respectively. The minimum operating time of the relays is 0.585 seconds.

B. Revised Simplex Employed on Segment A

Step 1: Convert the minimization problem to maximization problem by framing a dual of it, as shown in the above segment.
Thus we have:
Maximize Z=0.2y1+ 0.2y2+ 0.3y3
Subject to:
2.15y1 + 2.77y3 <= 2.15
2.15y2 – 2.15y3 <= 2.15

Step 2: Add slack variables:
LPP: Z=0.2y1+ 0.2y2+ 0.3y3+0S1+ 0S2
Constraints:
2.15y1 + 2.77y3 +S1= 2.15
2.15y2 – 2.15y3 +S2= 2.15

Step 3: The iterations of revised simplex for Segment A are as shown in Table 9, Table 10 and Table 11.

Table 9
Iteration 1 Using Revised Simplex Method for segment A

		C_j	0.2	0.2	0.3	0	0	Sol	Ratio	
Fixed ratio	Cb	BV	Y1	Y2	Y3	S1	S2			P
	0	S1	2.15	0	2.77	1	0	2.15	2.15/2.77	**2.77**
-1/2.77	0	S2	0	1	-1	0	1	1	-1	-1
		ΠY_j	0	0	0	0	0			
		C_j- ΠY_j	0.2	0.2	0.3	0	0			

Π= CbB-1 = [0 0][1 0; 0 1] = [0 0]
P= B-1 Y3 =[1 0; 0 1][2.77; -1] =[2.77; -1]

Table 10
Iteration 2 Using Revised Simplex Method for segment A

		C_j	0.2	0.2	0.3	0	0	Sol	Ratio	
Fixed ratio	Cb	BV	Y1	Y2	Y3	S1	S2			P
0	0.3	Y3	2.15	0	2.77	0.36	0	0.77	ND	**0**
	0	S2	0	1	-1	0.36	1	1.77	1.77	-1
		ΠY_j	0.232	0	5.95	0.038	0			
		C_j- ΠY_j	-0.15	0.2	-0.565	- 0.038	0			

Π= CbB-1=[0.3 0][1/2.77 0; 1/2.77 1]=[0.108 0]
P= B-1 Y2=[0.361 0 ; 0.361 1][0; 1]=[0 ; 1]

Table 11
Iteration 3 Using Revised Simplex Method for segment A

		C_j	0.2	0.2	0.3	0	0	Sol
Fixed ratio	Cb	BV	Y1	Y2	Y3	S1	S2	
0	0.3	Y3	2.15	0	2.77	0.361	0	0.77
	0.2	Y2	1	1	-1	0.361	1	1.77
		ΠY_j	0.232	0.2	4.79	0.038	0	
		C_j- ΠY_j	-0.15	0	-0.531	- 0.038	0	

Π= CbB^{-1}
= [0.3 0.2][1/2.77 0; 1/2.77 1]
= [0.108 0]

Therefore, the values of Y3 and Y2 turn out to be 0.77 and 1.77 respectively. The minimum operating time of the relays is 0.585 seconds.

C. Dual Simplex Employed on Segment B

Step 1: Convert the minimization problem to maximization problem by taking the dual of the problem
Maximize Z= -2.15 x1 - 2.15 x2 - 2.15 x3 - 2.15x4

Step 2: Convert the ≥ type constraints to ≤ type constraints and add surplus variables, S1, S2, S3, S4, S5, S6 and S7.
Maximize Z*(=-Z) = -2.15x1- 2.15x2 - 2.15x3 - 2.15x4 + 0S1 + 0S2 + 0.S3 + 0S4 + 0S5 + 0S6+0S7.
Subject to:
-2.15 x1 ≤ -0.2, -2.15x1+S1=-0.2
-2.15 x2 ≤ -0.2, - 2.15x2+s2=-0.2,
-2.15 x3 ≤ -0.2, - 2.15x3+S3=-0.2,
-2.15 x4 ≤ -0.2, - 2.15x4+S4=-0.2,
-1.75x1+1.47 x2 ≤ -0.3,
-1.75x1+1.47x2+S5 = -0.3,
-1.47x2+1.47x3 ≤ -0.3,
-1.47x2+1.47x3+S6=-0.3
-1.47x3+2.15 x4 ≤ -0.3,
-1.47x3+2.15x4+S7=-0.3

The first iteration using dual simplex for segment B is as shown in Table 12. After 4 iterations, we get the final values:
x1=0.629 x2=0.544 x3=0.34 x4=0.093
Z= 3.453
Hence, the TMS values in seconds of the relays are R1 = 0.629, R2 = 0.544, R3 = 0.34 and R4 = 0.093.
Further, the minimum operation time is 3.453 seconds.

Table 12
Iteration 1 using dual simplex method for Segment B

		C_j	-2.15	-2.15	-2.15	-2.15	0	0	0	0	0	0	0
C_b	BV	Xb	X1	X2	X3	X4	S1	S2	S3	S4	S5	S6	S7
0	S1	-0.2	-2.15	0	0	0	1	0	0	0	0	0	0
0	S2	-0.2	0	-2.15	0	0	0	1	0	0	0	0	0
0	S3	-0.2	0	0	-2.15	0	0	0	1	0	0	0	0
0	S4	-0.2	0	0	0	-2.15	0	0	0	1	0	0	0
0	S5	-0.3	-1.75	1.47	0	0	0	0	0	0	1	0	0
0	S6	-0.3	0	-1.47	1.47	0	0	0	0	0	0	1	0
0	S7	-0.3	0	0	-1.47	2.15	0	0	0	0	0	0	1
Z_j			0	0	0	0	0	0	0	0	0	0	0
Z_j-C_j			2.15	2.15	2.15	2.15	0	0	0	0	0	0	0
Z_{j-Cj}/Xb chosen				-1.22	1.4625	0	0	0	0	0	0	0	0

VI. CONCLUSION

This paper proposes the solution of the problem of overcurrent relay coordination in case of micro-grid in grid connected mode through dual simplex and two-phase algorithm. The analysis has obtained similar results for both the Dual Simplex and the Two-phase method. However, in case of two phase method, the number of iterations required is more than that of dual simplex method and it involves complex coding. Thus, these conventional algorithms are conveniently employed for protecting selected microgrid configuration.

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