DESIGNING A COORDINATED PROTECTION SYSTEM FOR MICROGRIDS ENABLED WITH DERS BASED ON UNIDIRECTIONAL FCL

Mohamad Mehdi Khademi
Hormozgan electrical distribution company
Khademi366@gmail.com

ABSTRACT

Introduction of Distributed Energy Resources (DERs) in a microgrid raises the fault currents, changes the radial topology of this system and may jeopardize the protection coordination. A framework is developed in this paper to design a protection system based on the commonly used Over Current Relays (OCRs) and Unidirectional Fault Current Limiters (UFCLs). An UFCL is used as the interface between the microgrid and the main distribution system. The PC design is tried to remain robust against changing the connection mode of the DERs. The sum of primary and backup operation times is considered as the objective function. OCRs' type selection parameters, OCRs' settings and UFCL characteristics are the optimization variables. To ensure the full PC, different constraints such as Coordination Time Interval (CTI) constraint are also considered. The Grey Wolf Optimization (GWO) algorithm is applied to solve the optimization problem.

1. INTRODUCTION

A framework is developed in this paper to find the optimal design of the protection system in a microgrid enabled with Distributed Energy Resources (DERs) with different connection modes. The DERs raises the fault currents in a microgrid. They disturb the radial topology of the network. The fault currents also vary due to different connection modes of DERs. These phenomena jeopardize the Protection Coordination (PC).

A method to find the optimal location of DERs and protection devices which maximize the PC level was proposed in [1]. However, multiple connection modes of DERs and OCRs' design parameters were not included. Reference [2] discussed the changes needed due to fault current bi-directionality, and over current protection coordination failure. The effects of integration of large number of DERs on protective device coordination were discussed in [3]-[5], where an adaptive protection scheme was suggested. Such design requires a decision unit, adaptively adjustable setting of OCRs and a strong communication system. In [6], the penetration level of the DERs' was maximized considering the PC constraints. To limit the short-circuit currents and the range of change in short-circuit currents, one approach is optimal locating and sizing of fault current limiters (FCL) in a microgrids [7]-[8].

The main focus of this paper is on finding the optimal design of the protection system. In distribution system, the protective devices include Over-Current Relays (OCRs), fuses, switches and disconnectors. Such protection system is almost sufficient for a redial distribution system. However, due to three phenomena mentioned, additional devices would be necessary to hold PC, when DERs are added to the system. Here, a solid-state Unidirectional Fault Current Limiter (UFCL) is designed to be installed as an interface between the microgrid and the main distribution network. This UFCL limits microgrid share in fault current during the utility (main system) faults. However, in order to increase the short circuit level in the microgrid, this UFCL does not limit the current during the microgrid disturbances. The higher short circuit capability leads to lower voltage sag during a high impedance fault, starting of a motor load and other disturbances. References [9] and [10] provided a solid state FCL design suited for such application.

In this paper, the main objective is to increase the PC as much as possible. The sum of primary and backup operation times (for different fault locations and different connecting modes) is considered here as the objective function. According to the historical data a time weight is assigned to each connecting mode. The main protective devices are OCRs. The OCRs' type selection parameters (parameters of the inverse-time operation characteristics), OCRs' settings (time setting and pickup current setting), and UFCL characteristics (real and imaginary parts of UFCL impedance) are the optimization variables. To ensure the full PC, the Coordination Time Interval (CTI) constraint for each primary-backup pairs is included in the formulation. Though the main focus is on the planning problem (selecting the OCRs and finding the proper design of UFCL), the OCRs' time and current settings (which are adjustable in the future) are also optimized here to find a practical solution for the planning problem.

The multiple connection modes for DERs are the main cause of PC failure. In a distribution system enabled with DERs it is quite possible that the primary-backup role of two OCRs for one fault is swapped for the other one. As will be discussed this is the other cause of PC failure. The UFCL coordinates the operation of the main distribution system OCRs and the microgrid OCRs. The proposed framework is tested on a practical system. Different case studies are conducted on this microgrid. The results show the effectiveness of the proposed framework to find the proper design of the coordinated protection system for the DER enabled microgrid.

The Grey Wolf Optimization (GWO) algorithm [11] is applied to find the OCRs' type selection and setting parameters as well as the UFCL design parameters which hold the PC during all connection modes.

The rest of this paper is organized as follows. The PC formulation is presented in Section 2. Section 3 gives an overview of GWO algorithm. Numerical results are provided in Section 4. The conclusion is drawn in Section 5.

2. PC PROBLEM

OCRs are the well-known devices used in sub-transmission and distribution system protection. Operation time of each OCR is determined based on the characteristic curve of this OCR and the fault current intensity. For a fault f, (1) gives the operation time of OCR$_i$, where $I_{f,i,j}$ is the fault current measured by the relay CT. The time Dial Setting and pick-up current of OCR$_i$ are given by TDS_i and $I_{pickup,i}$, respectively. Parameters α_i, β_i and ρ_i are the type selection variables for OCR$_i$.

$$t_{ij} = \left(\frac{\alpha_i}{\left(\frac{I_{f,i}}{I_{pickup,i}} \right)^{\rho} - 1} + \beta_i \right) TDS_i \qquad (1)$$

For a microgrid with N^c connection modes (for the system DERs) indexed by c and N_f faults indexed by f, (2)-(10) optimize the PC and give the planning and operation parameters of each OCR. Though the planning parameters are the main design variables, operation of the protection system and therefore, the operation parameters should be also considered to select the OCRs that hold the PC in all connection modes. There are 5 optimization variables for each OCR and 2 optimization variables regarding the UFCL used as the interface between the microgrid and the main distribution system. For a system with 10 OCRs (like the one presented in Fig. 1) the number of optimization variables would be 52. The objective function is the sum of OCRs' operation times in different connection modes for different faults (2). According to the historical data a Duration Weight (DW) is assigned to each connection mode. Equation (3) gives this weight for connection mode c. For fault f and connection mode c, the primary and backup OCRs are given by PR_f^c and BR_f^c, respectively.

$$\underset{\alpha,\beta,\rho,I_{pickup},X,R}{\text{Min}} \quad Obj = \sum_{c=1}^{N^c} DW_c . \sum_{f=1}^{N_f} t_{c,PR_f^c} + t_{c,BR_f^c} \qquad (2)$$

$$DW_c = \frac{D_c}{\sum_{c=1}^{N_c} D_c} \qquad (3)$$

Due to the non-radial topology of the system, it is possible to have more than one primary-backup pair for a certain fault. In order to consider all the system relays, each primary-backup pair has been counted once in N_f in this formulation.

$$t_{c,PR_f^c} = \left(\frac{\alpha_{PR_f^c}}{\left(\frac{I_{c,f,PR_f^c}}{I_{pickup,PR_f^c}} \right)^{\rho_{PR_f^c}} - 1} + \beta_{PR_f^c} \right) TDS_{PR_f^c} \qquad (4)$$

$$t_{c,BR_f^c} = \left(\frac{\alpha_{BR_f^c}}{\left(\frac{I_{c,f,BR_f^c}}{I_{pickup,BR_f^c}} \right)^{\rho_{BR_f^c}} - 1} + \beta_{BR_f^c} \right) TDS_{BR_f^c} \qquad (5)$$

For each fault in each connection mode, no trip command should be issued by other OCRs sooner than issuing the trip command by the primary and backup relays regarding this fault (6). For all the primary and backup relays, the operation time should be lower than a predefined value (7). Coordination time interval constraints are given in (8).

$$t_{\min} \le t_{c,PR_f^c} < t_{c,i,f} \qquad \forall i \ne PR_f^c$$
$$t_{\min} \le t_{c,BR_f^c} < t_{c,i,f} \qquad \forall i \ne PR_f^c,\ BR_f^c \qquad 6)$$

$$t_{c,PR_f^c} \le t^{\max}$$
$$t_{c,BR_f^c} \le t^{\max} \qquad (7)$$

$$0.2 \text{ sec} \le t_{c,PR_f^c} - t_{c,BR_f^c} \le 0.5 \text{ sec} \qquad (8)$$

Equation (9) gives the lower and upper bounds of the time delay setting of OCR$_i$. Finally, the lower and upper bounds of the pickup current of this OCR is given in (10). The lower bound and upper bound of real and imaginary part of UFCL impedance should be also included in the problem formulation based on [10].

$$TDS_{i,\min} \le TDS_i \le TDS_{i,\max} \qquad (9)$$

$$I_{pickup,i}^{\min} \le I_{pickup,i} \le I_{pickup,i}^{\max} \qquad (10)$$

For the system analyzed in Section 4, the IEEE standard inverse-time overcurrent relays are used and the lower and upper bounds on time dial setting of the OCRs are therefore determined according to the related IEEE standard [12].

To determine the lower and upper bounds of the pickup current of the OCRs the system characteristics should be taken into account. The pickup current should be above the maximum load current measured by the CT. Based on the common practice $I_{\text{pickup},i}$ is considered to be no lower than $1.25I_{i,\max}$. To ensures OCR operation for all the faults, pick up current should be lower than the minimum fault current ($I_{\text{pickup}}<I_{\text{f,min}}$). The fault current associated to a line to line fault at the remote end of the feeder in light loads is the minimum fault current for the radial grids. It is better to

determine the lowest fault current for each relay based on the historical data or the current rating of the system equipment. On the other hand, relay manufacturers do not guarantee the accuracy for the fault currents lower than $1.5I_{\text{pickup}}$. In such condition, it is better to set $I_{i,\text{pickup}}$ lower than $0.67I_{i,f,\min}$, if it is possible according to the lower bound constraint on $I_{i,\text{pickup}}$.

The GWO algorithm (Section 3) is used here to find the solution of the optimization problem presented in (2)-(10). The problem constraints (7)-(9) are modeled as the parameter-free penalty functions ($p1$-$p8$). These functions should be appended to the objective function (2) to form the fitness function (11).

$$\begin{aligned} FF_1 = \sum_{c=1}^{N_c} DW_c . \sum_{f=1}^{N_f} [t_{c,PR_f^c} + t_{c,BR_f^c} \\ + p1_{c,f} + p2_{c,f} + p3_{c,f} + p4_{c,f} \\ + p5_{c,f} + p6_{c,f} + p7_{c,f} + p8_{c,f}] \end{aligned} \quad (11)$$

$$p7_{c,f} = \begin{cases} M_7.[0.2 - t_{c,PR_f^c} + t_{c,BR_f^c}] & t_{c,PR_f^c} - t_{c,BR_f^c} \le 0.2 \\ 0 & \text{otherwise} \end{cases} \quad (12)$$

$$p8_{c,f} = \begin{cases} M_8.[t_{c,PR_f^c} - t_{c,BR_f^c} - 0.5] & 0.5 \le t_{c,PR_f^c} - t_{c,BR_f^c} \\ 0 & \text{otherwise} \end{cases}$$

There are 8 different penalty functions each of which regarding to one inequality constraint. As an example, two penalty functions should be defined to handle the constraints presented in (8). These penalty functions are presented in (12). As can be seen, the value of each constraint violation is multiplied by the regarding big constant (M) to raise the value of objective function proportional to the constraint violation. This scheme pushes the infeasible solutions towards the feasible region of the optimization algorithm.

3. GREY WOLF OPTIMIZATION ALGORITHM

The GWO algorithm mimics the hierarchical hunting mechanism of grey wolves in wildlife [11]. Four types of grey wolves such as alpha (mostly responsible for making decisions), beta (wolves that help the alpha in decision-making), delta (subordinate), and omega (last wolves that are allowed to eat) are employed for simulating the leadership hierarchy. Three steps of hunting are implemented in GWO algorithm to perform optimization, i.e. searching for preys, encircling prey, and attacking prey.

3.1. Encircling prey

During the hunt, grey wolves encircle prey. Equations (13) and (14) model such behavior. The current iteration is given by I and A and C are the coefficient vectors that determine the search direction. Adjusting these vectors and considering the current position of a wolf, different places around the best agent can be reached. The position of the grey wolf and the pray are given by X and X_p, respectively. The coefficient vectors are found using (15). Components of a decreases linearly from 2 to 0 over the iterations and r_1, r_2 are random vectors in [0, 1].

$$D = \left| C.X_p(k) - X(k) \right| \quad (13)$$

$$X(k+1) = X_p(k) - A.D \quad (14)$$

$$\begin{aligned} A &= 2a.r_1 - a \\ C &= 2r_2 \end{aligned} \quad (15)$$

3.2. Hunting

In the search for prey, we usually have no idea about its the location. In hunting process of grey wolves, the alpha, beta and delta have better knowledge of the potential location of prey. The first three best solutions are stored and the other agents update their positions based on the position of the position of the leading wolves using (16)-(18).

$$\begin{aligned} D_\alpha &= \left| C_1.X_\alpha - X \right| \\ D_\beta &= \left| C_2.X_\beta - X \right| \\ D_\delta &= \left| C_3.X_\delta - X \right| \end{aligned} \quad (13)$$

$$\begin{aligned} X_1 &= X_\alpha - A_1.(D_\alpha) \\ X_2 &= X_\beta - A_2.(D_\beta) \\ X_3 &= X_\delta - A_3.(D_\delta) \end{aligned} \quad (14)$$

$$X(t+1) = \frac{X_1 + X_2 + X_3}{3} \quad (15)$$

3.2. Attacking prey and exploration

As the prey stops moving, grey wolves attack the prey and the hunt ends. To model approaching the prey, the value of a decreases from 2 to 0. The grey wolves diverge from each other to search for prey and converge to attack the prey. In order to model the diversion and to avoid stagnating in local optimal solutions, exploration mechanism is included in GWO algorithm. With $|A|>1$, the wolves diverge the prey to find a better prey and with $|A|<1$, they attack the prey.

4. NUMERICAL RESULTS

In this section, the case studies are conducted on the microgrid presented in Fig. 1. The rest of system is modeled by an equivalent Thevenin model. Table (1) gives the data on the system equipment. Connection mode 1, 2 and 3 are equivalent to no DG, only DG1 connected, and both DGs connected, respectively. Table (2) shows the primary-backup pairs for these connection modes. Some primary OCRs doesn't have any backup OCR. The duration the connection modes are considered to be equal. The lower and upper bounds of TDS are 0.05 and 11, respectively. For all the OCRs, the CT ratio is 5:100.

Table (1)
System data

Thevenin model	V_L=12.66 kV, S_{sc}=100 MVA, X/R=5
$Z_{feader\ 3}$	Over-head Line: R=0.7 Ω, X=2 Ω
Z_1-Z_3	Over-head Line: R=1 Ω, X=3 Ω
Z_{MG}	Over-head Line: R=0.5 Ω, X=1.5 Ω
Z_{MG1}-Z_{MG3}	Over-head Line: R=0.5 Ω, X=1 Ω
DG1-DG2	300 kVA, R_{DG}=0.08 Ω, X_{DG}=0.07 Ω
Transformers T1-T3	12.66/0.4, 1 MVA, R_T=0.05 Ω, X_T=0.07 Ω
Non-Rotating Loads L_{47}-L_{50}	S=300 kVA, PF=0.95 lag
Non-Rotating Load L_{MG1}	S=150 kVA, PF=0.95 lag
Non-Rotating Load L_{MG2}	S=150 kVA, PF=0.97 lag
Sensitive Non-Rotating Load L_{MG3}	S=200 kVA, PF=0.96 lag

Table (2)
Primary-Backup pairs

Fault location	Connection mode 1		Connection mode 2		Connection mode 3	
	Primary OCR	Backup OCR	Primary OCR	Backup OCR	Primary OCR	Backup OCR
Bus 2	OCR_1	--	OCR_1	--	OCR_1	--
			OCR_{MG}	OCR_6	OCR_{MG}	OCR_6
					OCR_{MG}	OCR_7
Bus 3	OCR_2	OCR_1	OCR_2	OCR_1	OCR_2	OCR_1
			OCR_2	OCR_{MG}	OCR_2	OCR_{MG}
Bus 4	OCR_3	OCR_2	OCR_3	OCR_2	OCR_3	OCR_2
MG	OCR_{MG}	OCR_1	OCR_{MG}	OCR_1	OCR_{MG}	OCR_1
					OCR_6	--
			OCR_7	--	OCR_7	--
MG1	OCR_5	OCR_{MG}	OCR_5	OCR_{MG}	OCR_5	OCR_{MG}
					OCR_5	OCR_6
			OCR_5	OCR_7	OCR_5	OCR_7
MG2	OCR_6	OCR_{MG}	OCR_6	OCR_{MG}	OCR_6	OCR_{MG}
			OCR_6	OCR_7	OCR_6	OCR_7
MG3	OCR_7	OCR_{MG}	OCR_7	OCR_{MG}	OCR_7	OCR_{MG}
					OCR_7	OCR_6

The best selection and setting parameters of the OCRs are found next in order to optimize the PC. Based on the results obtained in this study, it is not possible to hold the PC without a UFCL due to violation of some unacceptable coordination time interval constraints. There were some instances that coordination time intervals were even negative. This indicates that some backup protection were even faster than the primary protection. Therefore, a UFCL optimal design is also found along with the selection and setting parameters of the OCRs.

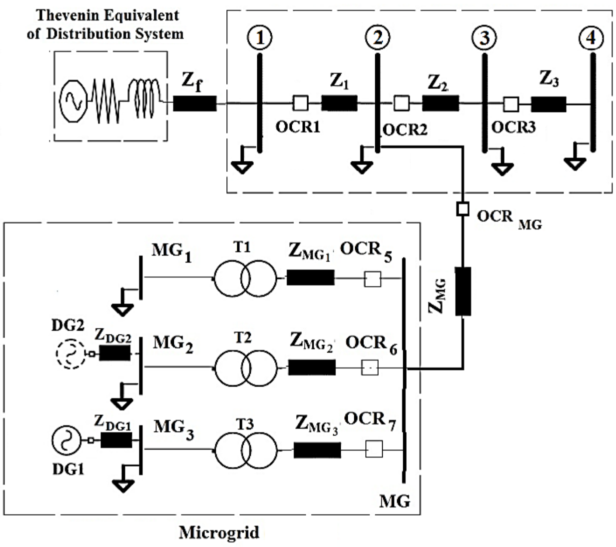

Fig. 1. The downstream and upstream systems.

With UFCL considered as the interface between the microgrid and the main distribution network, the full PC is realized. For the optimal solution found with GWO algorithm the real and imaginary parts of UFCL impedance are 10.1 and 19.6 Ω, respectively. Table (3) gives the OCRs' selection parameters. For connection mode 3, the operation times are given in Table (4). In this table the entries filled by "UFCL" indicate no necessity for backup protection due to the presence of the UFCL. This table shows that all the constraints are satisfied and PC is held for this connection mode. The result was the same for the other connection modes, but the detailed results are not included for these connection modes for the sake of brevity. The value of the PC objective function (11) is equal to 7.37 s.

Table (3)
OCRs selection parameters

Primary OCR	α	β	ρ
OCR_1	0.4	0.03	1
OCR_2	0.4	0.04	1
OCR_3	0.5	0.04	1
OCR_{MG}	0.7	0.02	2
OCR_5	0.7	0.02	2
OCR_6	0.5	0.03	2
OCR_7	0.5	0.03	2

Table (4)
Operation times of the OCRs

Fault	Primary	Backup	t_{PR}	t_{BR}	coordination time

	OCR	OCR			interval
2	OCR_1	--	0.150	--	--
	OCR_{MG}	OCR_6	0.178	UFCL	--
	OCR_{MG}	OCR_7	0.156	UFCL	--
3	OCR_2	OCR_1	0.176	0.376	0.200
	OCR_2	OCR_{MG}	0.187	UFCL	--
4	OCR_3	OCR_2	0.120	0.355	0.436
MG	OCR_{MG}	OCR_1	0.192	0.378	0.332
	OCR_6	--	0.063	--	--
	OCR_7	--	0.051	--	--
MG1	OCR_5	OCR_{MG}	0.021	0.221	0.200
	OCR_5	OCR_6	0.141	0.402	0.493
	OCR_5	OCR_7	0.148	0.376	0.48
MG2	OCR_6	OCR_{MG}	0.051	0.251	0.200
	OCR_6	OCR_7	0.172	0.388	0.417
MG3	OCR_7	OCR_{MG}	0.046	0.246	0.200
	OCR_7	OCR_6	0.162	0.362	0.200

4. CONCLUSIONS

DERs are integrated to current microgrids for different reasons such as environmental concerns and reliability improvement. However, with these DERs the system topology is no longer radial and the fault current levels increase. Both phenomena may jeopardize the protection coordination. The problem is more pronounced if varying connection status of DERs is also taken into account. In this paper, it was shown that even if the operator selects the OCRs' characteristics types, it is not possible to hold the full protection coordination and another device would be necessary. It was also shown that with a UFCL it is possible to hold the PC in a microgrid enabled with DERs with varying connection mode.

REFERENCES

A. Pregelj, M. Begovic, A. Rohatgi, 2006, "Recloser allocation for improved reliability of DG-enhanced distribution networks", *IEEE Trans. Power Syst.*, vol. 21, no. 3, 1442–1449.

J. C. Gomez, J. Vaschetti, C. Coyos, and C. Ibarlucea, 2013, "Distributed Generation: impact on Protections and Power Quality", *Latin America Trans., IEEE*, vol. 11, no. 1, 460-465.

S. M. Brahma and A. A. Girgis, 2004, "Development of adaptive protection scheme for distribution systems with high penetration of distributed generation", *IEEE Trans. Power Del.*, vol. 19, no. 1, 56–63.

H. Nikkhajoei and R. H. Lasseter, 2007, "Microgrid protection", in *Proc. IEEE Power Eng. Soc. Gen. Meet.*, 1–6.

M. Dewadasa, R. Majumder, A. Ghosh, and G. Ledwich, 2009, "Control and protection of a microgrid with converter interfaced micro sources", in *Proc. Int. Conf. Power Syst. (ICPS)*, 1–6.

V. R. Pandi, H. H. Zeineldin, and X. Weidong, 2013, "Determining Optimal Location and Size of Distributed Generation Resources Considering Harmonic and Protection Coordination Limits", *IEEE Trans. Power Syst.*, vol. 28, no. 2, 1245-1254.

M. Ebrahimpour, B. Vahidi, and S. H. Hosseinian, 2013, "A Hybrid Superconducting Fault Current Controller for DG Networks and Microgrids", *IEEE Trans. Applied Superconductivity*, vol. 23, no. 5.

W. K. A. Najy, H. H. Zeineldin, and W. L. Woon, 2013, "Optimal Protection Coordination for Microgrids With Grid-Connected and Islanded Capability", *IEEE Trans. Industrial Electronics*, vol. 60, no. 4, 1668-1677.

T. Ghanbari, and E. Farjah, 2013, "Unidirectional fault current limiter: an efficient interface between the microgrid and main network", *IEEE trans. Power Syst.*, vol. 1, no. 1, 1591-1598.

T. Ghanbari and E. Farjah, 2012, "Development of an Efficient Solid-State Fault Current Limiter for Microgrid", *IEEE Trans. Power Del.*, vol. 27, no. 4, 1829-1834.

S.A. Mirjalili *et al.*, 2014, "Grey Wolf Optimizer", *Advances in Eng. Soft.*, vol. 69, 46-61.

IEEE Standard Inverse-Time Characteristic Equations for Overcurrent Relays, 1996, IEEE Std. C37.112-1996.