INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH & DEVELOPMENT

ISSN 2278 – 0211 (Online)

A Protection Coordination Index for Evaluating Distributed Generation Impacts on Protection for Meshed Distribution Systems Using Hybrid GA-NLP Approach

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Abstract:
The current distribution system can accommodate a limited number of distributed generation(DG) due to voltage profile and short circuit variations which consequently affect the power quality and protective relaying and the situation becomes sever with the increase in the DG penetration level. The amount of DG penetration can be limited by the conductor ampacity, voltage regulation and short circuit currents.
A new approach is proposed to determine the "protection coordination index" (PCI), which can serve as an effective measure when planning the protection of the meshed distribution system with DG. In this paper a hybrid genetic algorithm (GA) – nonlinear programming (NLP) is proposed to determine the PCI. The initial value of time dial setting (TDS) pickup current (Ip) of the relay is determined using GA technique and finding the final value using NLP method. The PCI is determined by optimally calculating the variations in the maximum DG penetration level with changes in the protection coordination time interval. This study is done on the distribution section of IEEE-14 bus system and analysis on how the capacity, type and location of DG can have an impact on protection coordination of directional over-current relay for meshed distribution system is determined.

Keywords: *Genetic algorithm, nonlinear programming, distributed generation, optimization, protection coordination*

1. Introduction

Distributed generation (DGs) are defined as electrical power generating units that are: small size which may vary from few kilowatts to megawatts, installed at an electrical load centers and owned by customers, independent power producers, and/or utilities. The current distribution system can accommodate limited numbers of DG due to voltage profile and short circuit variations which consequently affect the power quality and protective relaying. The amount of DG penetration can be limited by the conductor ampacity, voltage regulation and short circuit currents. New techniques are needed and essential to determine the maximum amount of DG that could be installed without requiring major changes to the distribution network. The maximum amount of active power that can be supplied by the DG at each bus of a radial distribution system, taking into account voltage violations, was determined using repetitive power flow studies. In addition, an index is proposed to help utility managers in identifying which DGs are responsible for the voltage violation. Analytical expressions for simple radial distribution system were developed to determine the allowable DG penetration considering conductor ampacity and voltage rise.

Protection device coordination for distribution systems can be affected, as well, by the integration of DG. Synchronous based DG has a much more profound effect on protection co-ordination than inverter based DG. The impacts of inverter based DG on re-closer/fuse coordination were investigated with inverter based DG and a DG interface control was proposed to mitigate such impact. A method that relies on optimally locating fault current limiters to minimize the impacts of DG on protection coordination in radial distribution systems was proposed and solved using particle swarm optimization. Due to the integration of DG and the recent drive to-wards smart grids, distribution systems are expected to be more of the meshed structure. A new hybrid structure allowing both radial and meshed operation of the distribution system is proposed to increase DG penetration. Identifying the impact of DG penetration for looped distribution systems on protection coordination problem with directional over-current relays is more complicated and has not been addressed in previous literature.

In this paper the problem of determining the optimum values of TDS and Ip of directional over current relays is formulated as a nonlinear programming problem and hybrid GA-NLP approach is proposed to find the optimum solution. GA has a drawback of sometimes, conversing to the values which may not be optimum, and NLP methods, being trapped in local optimum point, if the initial choice is nearer to the local optimum. NLP method gives global optimum solution, if proper initial choice is made. GA has been used to determine the initial value of TDS and Ip of directional OCRs. These values are then used as initial choice in NLP method and the maximum change in DG penetration level to the change in coordination time interval is used to determine the PCI.

2. Genetic Algorithm and Non-Linear Programming

GA is based on Darwin's theory of "survival of the fittest". GA is an optimization technique inspired by the principle of natural evolution and natural selection. GA allows a population composed of many solutions to evolve under specified rules to a state that maximizes the "fitness". GA begins, like any other optimization algorithm, by defining the optimization variable and the fitness function/objective function and ends like other optimization algorithms by testing for convergence. The convergence criteria in GA can be taken as the specified number of iteration.

The basic operation of the natural genetics- reproduction, crossover, and mutation, are implemented during numerical optimization using GA. "Reproduction is the process in which the individuals are selected on their fitness values relative to that of the population. The population is shorted according to the fitness of the chromosome. The individual chromosome with higher fitness values are selected for mating and subsequent genetic action. Consequently, highly fit individuals live and reproduce, and less fit chromosomes die. The reproduced chromosomes, which are used for mating are called parent chromosome. After the reproduction the "crossover" operation is implemented. Crossover is an operator that forms two new chromosomes, called "offsprings", form two parent chromosomes by combining part of information from each. First, two individuals string are selected for the mating pool generated by the reproduction operation and secondly a crossover site is selected at random along the string length, the binary digits are swapped between the two strings following the crossover site. The offsprings obtained from crossover, along with the parent chromosome, forms the new population. The "mutation" is applied after crossover. The mutation is the occasional, random alternation of binary digits in a string. Thus in mutation, a 0 is changed to 1, and vice versa, at a randomly selected location within the chromosome.

GA basically finds the optimum of an unconstrained problem. To solve a constrained optimization, we need to transform the original constrained problem into an unconstrained problem. Transformation methods are the simplest and most popular optimization methods of handling constraints. The constraints can be included in the objective function with the help of penalty method.

In an optimization problem, if the objective function and constraints are nonlinear, the problem is called NLPP. In case of OCR coordination problem the relay characteristic is nonlinear in nature because of which the objective function, the operating time constraints, and the coordination constraints become nonlinear.

3. Approach to Determine Protection Coordination Index

Due to the bidirectional fault current flow, directional overcurrent relays (OCR) are used for protecting looped distribution systems. The operating time (t) of a directional OCR is an inverse function of the short circuit current flowing through it. The function is defined by two parameters, namely the time-dial setting TDS) of the relay and the pickup current (I_p), which is the minimum value of current above which the relay will start to operate. The relay time-current characteristics can be expressed as follows:

$$t_{ij} = TDS_i * \frac{A}{(I_{scij}/I_{pi})\char`^B - 1}$$

Where,iis the relay identifier and jis the fault location identifier. AandB are constant that vary with the type of OCR which are set to 0.14 and 0.02, respectively. The term I_{scij}represents the relay short circuit current and $I_p$represents the relay pickupcurrent.

The protection coordination index, PCI, is defined as the rate of change of the maximum DG penetration level with respect to the rate of change of coordination time interval CTI. To determine the PCI, a two-phase protection coordination optimization model is proposed for looped distribution systems with directional over-current relays. In Phase I, the settings of the relays are determined using the conventional protection coordination (CPC) optimization model and with no DG present in the systems. The initial value for the NLP is determined using GA method .Various methods have been proposed to optimally solve the CPC model which includes, genetic algorithms, evolutionary algorithm, MATLAB optimization toolbox and particle swarm optimization. The outputsof phase I are the optimal relay settings which include the time- dial and the pickup current settings. These settings are inputted to Phase II as parameters where the main objective is to determine the maximum allow-able DG penetration level considering protection coordination and relay operating time constraints.

4. Conventional Protection Coordination Formulation

The settings of the relay are commonly calculated by formulating an optimization model where the main objective is to minimize the sum of relay operating time (T) subject to protection coordination, relay setting and relay operating time constraints. The main optimization variables are the relay settings which include the TDS and $I_p$as well as the total relay operating time. This model will be denoted as the CPC formulation and can be expressed as follows:

$$Minimize\ T = \sum_{i=1}^{N}\sum_{j=1}^{M}(t_{ij}^{p} + t_{ij}^{b})$$

Where N is the total number of relays and M is the total number of fault locations investigated. Variables t_{ij}^{p} and t_{ij}^{b} represent the primary relay i operating time and the backup relay i operating time for fault at location j respectively. The CPC formulation includes protection coordination constraints such that in case a primary relay fails to isolate the fault in its zone, a backup relay will operate. To assure proper coordination, a minimum gap in time between the operation of primary t_{ij}^{p} and backup relays t_{ij}^{b} , known as the CTI, needs to be maintained. The protection coordination constraint can be expressed as follows:

$$t_{ij}^{b} - t_{ij}^{p} \geq CTI$$

In addition to the above, there are upper and lower bound constraints on the relay settings and relay operating time which can be expressed as follows:

$$I_{pi-min} \leq I_{pi} \leq I_{pi-max}, \forall i$$

$$TDS_{i-min} \leq TDS_{i} \leq TDS_{i-max}, \forall i$$

$$0 \leq t_{ij}^{p}, t_{ij}^{b} \leq t_{ij-max}, \forall i, j$$

Where $I_{pi-min}$and I_{pi-max} are the lower and upper limits on the relay pickup current setting and TDS_{i-min} and TDS_{i-max} are the lower and upper limits on the relay TDS setting which are set to .025 to 1.1, respectively. The parameter t_{ij-max} represents the maximum relay operating time which will depend on the utility operator design criterion.

5. DG Maximization Formulation

In phase II, the relay settings (TDS) and (I_P) are treated as fixed parameters with values calculated form phase I. The proposed approach calculates the PCI by optimally determining the change in maximum achievable penetration level with CTI. In phase II, the main objective is to maximize the DG penetration (P) as follows:

$$Maximize\ P = \sum_{k=1}^{L} SDGK$$

Where S_{DGK} is the DG MVA ratings to be installed at bus K and L denotes the number of DG. Similarly, constraints

$$t_{ij}^{b} - t_{ij}^{p} \geq CTI$$

$$0 \leq t_{ij}^{p}, t_{ij}^{b} \leq t_{ij-max}, \forall i, j$$

are included in the problem formulation. In phase I, since there are no DG units in the distribution system, the short circuit currents are calculated and are inputted as parameters. On contrary, for phase II, the short circuit currents vary depending on the DG location and capacity. Inserting DG at certain locations affect the bus admittance matrix which in turn changes the bus impedance matrix resulting in variation in short circuit current values. Thus, the short circuit current is a function of the DG capacity as follows:

$$I_{scij} = f(S_{DGK})$$

In addition, an upper limit is set on the DG capacity that can be installed at each DG bus as follows,

$$0 \leq S_{DGK} \leq S_{DGK-max}, \forall k$$

Where $S_{DGK-max}$ represents the upper limit on the DG capacity to be installed at each location. The value of $S_{DGK-max}$ will depend on the utility planner design preference. The DG penetration level P is calculated for different values of CTI and the rate of change of P (ΔP) with respect to the rate of change of CTI (ΔCTI) is calculated to determine the PCI. Thus, the PCI index can be defined as follows:

$$PCI = -\frac{\Delta P}{\Delta CTI}$$

The units of PCI are in MVA/s. The PCI is defined such that a positive value indicates that a reduction in CTI will result in an increased in the DG penetration. Higher the values for PCI at certain location indicate that higher DG penetration levels can be achieved with less impact on protection coordination.

6. Application of Hybrid GA-NLP Approach to Determine PCI

The problem of optimum coordination of OCRs is formulated as NLPP. After formation of the problem, few generations of GA are used to determine the TDS and Ip of OCRs. These values are then used as initial choice in NLP methods, which gives the global optimum solution. For applying GA technique to find the initial solution, the problem is first converted into unconstrained optimization problem. As the objective function, coordination constraints and operating time constraints are written using relay characteristics, the relay characteristics constraints gets automatically incorporated in the objective function, coordination constraints and operating time constraints. The constraints due to operating time of relays, and the constraints due to coordination criteria, are included in the objective function using penalty method and thus the problem gets converted into an unconstrained optimization problem. Number of bits to represent each parameter is decided and then a population of suitable number of chromosomes is generated randomly. After this, the iterations of GA are started. The population is passed through the fitness function or objective function. Then the population is stored according to fitness. As the objective function is of minimization type the chromosomes giving the minimum value is most fit chromosome. This chromosome has been treated as elite chromosome. The chromosomes with higher fitness value survive and are called parent chromosomes. These are used for mating. Pairs of parent chromosomes are made for mating. Using the pairs of parent chromosome, crossover is performed. For each pair the crossover site is selected randomly. One pair (two parent chromosomes) generates two offsprings after crossover. All the parent chromosomes and all offsprigs are placed together to form the population for the next generation. The same population size is maintained in all generations. The mutation is applied after crossover. The number of mutations to be performed is decided by mutation rate, which is one of the GA parameters to be supplied at the beginning of the program. The bit to be mutated is selected randomly from the chromosome and is replaced by its compliment. At this point, an iteration of GA is complete. In this paper the stopping criteria have been considered as the number of iterations of GA, the process is stopped after performing pre-specified number of iterations. The elite chromosome, at this stage, gives the result.

After the initial solution is found with GA the final optimum solution of relay setting is found using NLP method. The function available in the MATLAB optimization toolbox, to solve the constrained nonlinear optimization problem, can be used to find the global optimum solution of the relay coordination problem. The results obtained, after performing pre-specified number of iterations of GA, are taken as the initial values of variables while applying NLP method. The final values of relay settings are used to determine the PCI.

7. Implementation of Proposed Method and Results

The single line diagram of the power distribution system of IEEE14-bus test system, where the power is fed from more than one point, is depicted in figure.

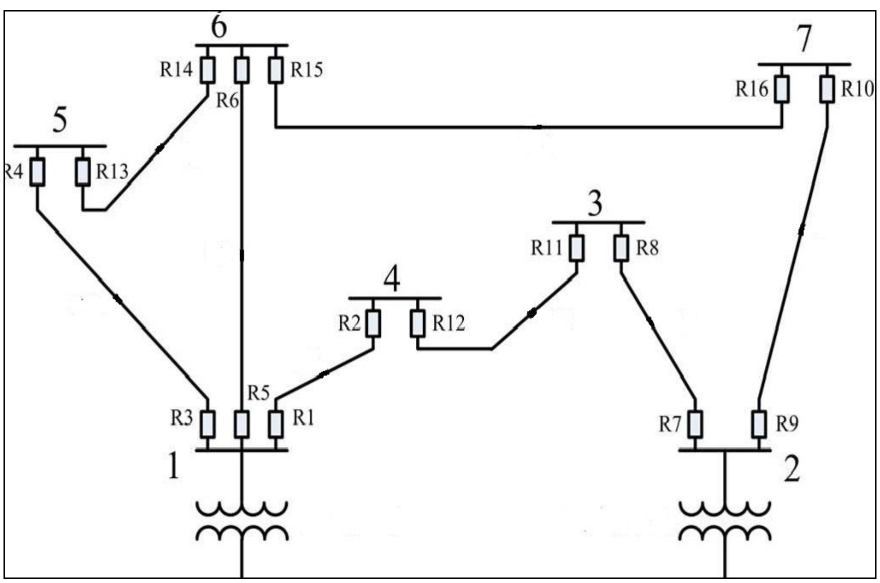

Figure 1: Power distribution system under study

The distribution system is fed though two 60MVA 132kv/33kv transformers connected at buses 1 and 2. All DG units are connected to the system through a 480V/33kv step-up transformer with 0.05 p.u transient reactance. The system is equipped with 16 directional over-current relays, two on each side of the line. The short circuit currents are calculated by conducting a bolted three-phase fault at the bus and the fault locations are at each bus. The relays are selected considering the near end fault and for fault at bus 1 relays R2, R4, R6 acts a primary relays and R11, R16, R14 acts as backup respectively. For fault at bus 2 relays R8 R10 acts as primary relays and R12 , R15 acts backups respectively. For fault at bus 3 relays R7, R12 acts as primary relays and R10 , R1 acts backup respectively. For fault at bus 4 relays R1, R11 acts as primary relays and R6 , R7 acts backup respectively. For fault at bus 5 relays R3, R14 acts as primary relays and R2 , R16 acts backup respectively. For fault at bus 6 relays R13, R5,R16 acts as primary relays and

R3, R2, R9 acts backup respectively. For fault at bus 7 relays R15, R9 acts as primary relays and R13, R8 acts backup respectively. Since the relays used is directional over current relay and will sense a fault current in the direction away from the buses.
The conventional protection coordination Phase I of the proposed algorithm is implemented to the primary power distribution section IEEE14-bus to minimize the total operating time T by choosing the optimal relay setting and operating time using GA. The outputs obtained from GA are used as an initial choice in the NLP method which gives a global optimum solution. Table 1 presents the optimal relay settings results using GA method which is used as an initial choice in the NLP method to obtain the global optimum solution.

Relay No.	TDS (s)	Ip (p.u)
1	0.081	0.9219
2	0.0644	0.0815
3	0.0275	0.0501
4	0.0132	0.2558
5	0.0899	0.2053
6	0.0812	0.05
7	0.0528	0.9897
8	0.0188	0.1241
9	0.0301	1.2246
10	0.0686	0.0593
11	0.0626	0.05
12	0.0868	0.3024
13	0.0884	0.3105
14	0.0182	0.3957
15	0.09	0.3779
16	0.0125	0.298

Table 1: Optimal Relay TDS and Ip Setting for test case system using GA

Relay No.	TDS (s)	Ip (p.u)
1	0.0125	1.8556
2	0.0744	0.05
3	0.0125	0.05
4	0.0125	0.05
5	0.0125	0.8225
6	0.0125	0.0727
7	0.0125	1.7491
8	0.0125	0.1339
9	0.0125	1.7225
10	0.0125	0.11
11	0.0125	0.05
12	0.0125	1.1164
13	0.1747	0.05
14	0.0125	0.41
15	0.0125	1.1825
16	0.0125	0.05

Table 2: Optimal Relay TDS and Ip Setting for test case system using NLP method

Also Table 3 presents the backup and primary relay pairs for faults form 1 to 7. The results are obtained for CTI=.3 s and maximum relay operating time of 2.5s. The TDS setting of the majority of relays, hits the lower bounds which is…..s. In addition it can be seen from Table 3 that the coordination constraints is binding for the majority of the faults locations.

Fault Location	**Operating times of relays in sec**	
	Primary	**Backup**
1	R4: 0.0361	R14: 0.3361
	R6: 0.0324	R13: 0.5053
2	R8: 0.0358	R12: 0.3358
	R10: 0.0322	R15: 0.3322
3	R7: 0.1051	R10: 0.4051
	R12: 0.1213	R1: 0.4213
4	R1: 0.1175	R6: 0.4175
	R11: 0.0220	R7: 0.3220
5	R3: 0.0198	R2: 0.3198
	R14: 0.0528	R5: 0.3528
6	R5: 0.0655	R2: 0.4040
	R16: 0.0221	R9: 0.3221
7	R9: 0.1029	R8: 0.4029
	R15: 0.1270	R3: 0.4270
Total Operating time(s) =6.1979		

Table 3: Optimal Primary and Backup relay operating times

The results presents in Table 2 will be inputted to Phase II of the optimization problem to determine the proposed PCI. The CTI is varied and for each value of CTI, the maximum DG penetration level at each candidate DG location is optimally determined. CTI is chosen from .2s to .29s and for each value of CTI and for each bus the maximum DG penetration is determined. The result of maximum DG penetration for each value of CTI form .2s to .29s for every DG bus candidate location is present in figure.

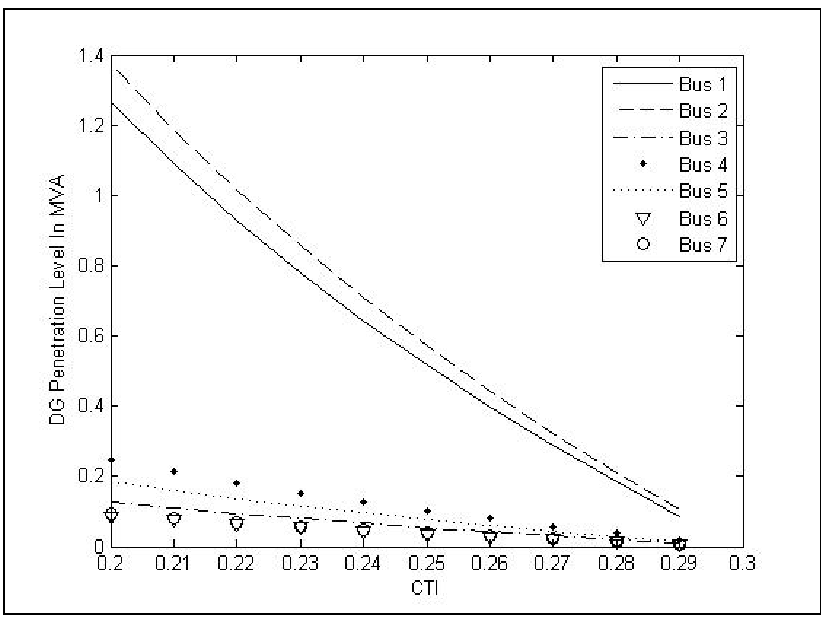

Figure 2: Variation of DG penetration with CTI

The PCI is the rate of change of the maximum DG penetration withrespect to CTI and the Table 4 presents the PCI values obtained. The locations with higher PCI results in lower DG impacts on protection coordination.

DG Bus	PCI (MVA/s)
1	13.10843
2	14.08071
3	1.311174
4	2.526921
5	1.889208
6	0.884166
7	0.944420

Table 4: PCI for the IEEE14 Bus with 7 DG candidate locations

8. Conclusion

This paper proposes a new protection coordination index (PCI) for quantifying impacts of interconnecting DG on protection coordination. The PCI is calculated by optimally determining the rate of change of DG penetration level with respect to the coordination time interval. A two-phase optimization problem is proposed, in which the initial relay settings are determined using the GA method and used as initial choices in NLP method to determine the global optimum solution which is implemented and tested on the primary power distribution section of IEEE 14-bus system. The results show that the proposed PCI can serve as an effective measure for utility owned DG with minimal impact on the protection coordination. Also, PCI can also help in determining the extent to which the system protection coordination is affected with the installation of customer owned DG and thus identifying any necessities for modifying the relay settings as result of the DG integration

9. References

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