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Preventing Loop Flows Using Fuzzy Set Theory and Genetic Algorithms

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Abstract-- **In the de-regulated power systems the loop flow control issue is becoming important. This is especially true when the transmission system is operated at or close to its limits. Thus, prevention and/or control of loop flows problem need be solved efficiently and fast. We suggest a fuzzy set theory based method using genetic algorithm to solve this problem. In the proposed method the constraints and objectives are handled in fuzzy environment and the optimization problem is solved using genetic algorithms. The proposed method is applied to IEEE 14 and 30 bus test systems and the results are presented.**

Index Terms—**Fuzzy set theory, Genetic Algorithms (GAs), Interconnected Power Systems, Loop Flow, Power Flow.**

I. INTRODUCTION

THE high power loses on transmission lines, low efficiencies, or the long path power travels through (occupying transmission lines) before arriving to the loads has not seen as an important problem in a government controlled power system. Since the rising costs due to power losses and inefficient operations etc. are directly adjusted to the customers' bill or are partly subsidized by the governments, the loop flows inherited in an interconnected power system was not seen as a serious problem [1].

After the privatization (de-regulation) the issues such as; how much power flows on which transmission lines, which company uses other's transmission lines and/or amount and time of the transmission line usage have become important.

If a system runs into a problem due to heavy line usage it is important to identify the responsible parties (unscheduled power flows). The path electrical energy takes depends on physical laws, i.e., Kirchhoff's current and resistance laws determine the path for the energy to flow. Energy takes the shortest path (in terms of resistivity) instead of a contracted path.

In this case a third party between a buyer and a seller of energy comes into picture. In such a case the question is, who is to pay for the transmission line usage between a seller and a buyer [2-6].

Our goal in this study is to develop a fuzzy set theory based method to prevent and/or control the loop flow [7-8] using genetic algorithms. We formulate the problem as a multi-objective optimization problem. In practice, one may tolerate to small variations of power systems variables (bus voltages, line currents etc.,) from their limit values. Thus, one of the best solutions to the problem at hand may be obtained by not-taking those small limit violations into account. Furthermore, one may reach to a better objective function with these violations. To what degree toleration and/or on which variable of power systems toleration is allowed depends on systems' operating conditions.

In recent years, there have been a lot of applications of fuzzy set theory to various power system problems [9-10]. In the past power system optimization problems were dealt with using non-linear and linear programming methods. The optimization problems under an uncertain environment can be reformulated using fuzzy sets. Many interesting applications of fuzzy sets in the optimization of the power system operating and planning stages have been reported [11]. With the advent of computational power and tools the researchers tried new methods such as genetic algorithms, evolutionary algorithms etc. on power system problems as well [12-13].

Aiming to improve power systems operation conditions and to control loop flows we tackle the problem in a fuzzy environment as a multi-objective function. Once problem is formulated we solve it using genetic algorithms, which will enable us in the future to solve the same problem in a multi-core environment. Doing so will enable the system operators in the future to use the developed tools in real-time. Since the power systems include thousands of buses resulting in large dimensional matrix operations needing the use of iterative solutions methods, the use of parallel environments and techniques will shorten the solutions time.

The rest of the paper is as follows: Section II introduces the loop flow problem, section III explains fuzzy set theory and fuzzy decision making whereas section IV explains genetic algorithms. We formulate the problem in section V, provide the test results in section VI and finally provide conclusions in section VII.

II. LOOP FLOW

In a closed-loop transmission network, when some amount of scheduled power flows through an adjacently connected system, a loop flow phenomenon occurs, see Fig. 1. It can also be referred to as the parallel path flow, unscheduled flow or circulating flow. The main reason of this phenomenon is that the Kirchhoff's current and resistance laws determine the path for the energy to flow. Several power flow cases could exist in a closed-loop transmission network depending on the system topology and operating conditions. Loop flows may cause congestion, increase the transmission losses, and increase in the transmission cost because of not using a contracted path.

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This can be best explained using Fig.1. System B buys power from system A, however, power travels through system C occupying different transmission lines. This is called loop flow. One needs to control (that is redirect the power to the transmission line directly connecting A and B) or prevent power flows between A and C.

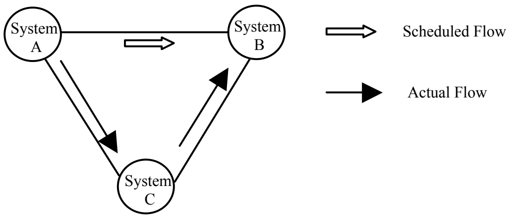

Fig. 1. A loop flow example.

III. FUZZY SETS AND FUZZY DECISION MAKING

This section summarizes the basic concepts of fuzzy sets used for the fuzzy model, and offers brief information about the multi-objective fuzzy model. The essentials of the technique for solving the multi-objective fuzzy model are also presented.

Fuzzy set theory is a generalization of traditional crisp set theory. The idea is to replace the concept that each variable has a precise value by the fuzzy concept that each variable is assigned a degree of membership for each possible value of the variable [7-8]. A fuzzy set in the universal set *U*, is a generalization of a classical set, and it can be characterized by a membership function, $\mu(x)$, that takes real values in the continuous interval [0,1]. A fuzzy set A_d in *U* can be represented by an ordered pair composed by a generic element *x* and its membership value, that is,

$$A = \left\{(x, \mu_A(x))\ x \in U\right\} \qquad (1)$$

In Fuzzy decision-making, fuzzy objective functions and constraints can be characterized by the membership function of the fuzzy objectives, $\mu_g(x)$, and the membership function of the fuzzy constraints, $\mu_c(x)$, respectively. The optimal solution, which is the fuzzy decision *D*, is given as an intersection of the fuzzy sets describing the constraints and the objectives. Using the membership functions, the overall membership function value is obtained as

$$\lambda = \min\left\lfloor \mu_g(x), \mu_c(x) \right\rfloor \qquad (2)$$

The optimal solution is defined to be the one with the highest degree of membership, and the optimization problem becomes that of maximizing the satisfaction with the solution, subject to the crisp and fuzzy constraints [11,14].

IV. GENETIC ALGORITHMS

Genetic algorithms are nature inspired stochastic search methods. Their mechanism is based on natural selection and natural genetics. Most stochastic search methods operate on a single solution to the problem at hand. Genetic algorithms operate on a population of solutions. An individual in a population is regarded as a string. The string regarded as chromosome consisting of n genes. The chromosome is called genotype of an individual. Each chromosome represents a possible solution to the problem that is being optimized. Each gene represents a value to each variable of the problem. Each gene could be either a binary or a floating-point number. We use the floating-point representation for each variable in our study to get rid of the discretization errors.

A genetic algorithm creates a population of chromosome randomly then applies crossover and mutation operators to the individuals in the population to generate new individuals. It uses various selection methods so that it picks the best individuals for mating (and subsequent crossover). The objective function (fitness function) determines how each individual is 'good'. Sometimes the objective function and the fitness function could be different depending on optimization problem whether minimization or maximization.

Two of the most common genetic algorithm implementations are 'simple' and 'steady state'. Goldberg describes the simple genetic algorithm in his 1989 book: *Genetic Algorithms in Search and Optimization*. It is a *generational* algorithm in which an entire population is replaced by each generation [15].

The genetic algorithm performs well on many different types of problems. But there are many ways to modify the basic algorithm, and many parameters.

A simple genetic algorithm is composed of three operators: Selection, crossover (reproduction), and mutation.

Selection methods: Rank selection, roulette wheel selection, tournament selection, stochastic remainder sampling, and stochastic uniform sampling.

The selection method determines how individuals are chosen for mating. If one uses a selection method, which picks only the best individual, then the population will quickly converge to that individual. So the selector should be biased toward the better individuals, but should also pick some that aren't quite as good.

Typically crossover is defined so that two individuals (the parents) are combined to produce two more individuals (the children).

The mutation operator introduces a certain amount of randomness. It can help the search to find solutions that crossover alone might not encounter. The mutation operator plays a very important role on escaping from local optima.

V. PROBLEM FORMULATION

In the proposed multi-objective model for an optimal operation of a power system, the objectives and constraints are modeled by fuzzy sets to represent practical situations in power system operation where the limits on specific variables are soft and the small violations of these limits may be tolerable. The main objectives to be considered are the control of line flows, prevention of the loop flows, and minimization of both active and reactive power losses of the system at hand. The problem is formulated as a multi-objective problem subject to operational and electrical constraints. The membership functions of both the objective functions and the constraints can be described in a trapezoidal form. The higher the value of a membership function implies a greater satisfaction with a solution. A membership function, $\mu_{PL}(P_L)$, which is considered for the active power transmission losses is shown in Fig. 2., where

$P_L^{undesired}$, represents the un-satisfaction limit for the total active power transmission losses. The degree of satisfaction for the objective is zero for any value of P_L greater than $P_L^{undesired}$. We want to keep the objective below an un-satisfaction limit. The system operators taking into account their experiences can determine these satisfaction limits on the membership function and system operation costs. The membership function $\mu_{PL}(P_L)$ is defined as

$$\mu_{PL}(P_L) = \begin{cases} 1 - \dfrac{P_L}{P_L^{undesired}} & P_L < P_L^{undesired} \\ 0 & P_L > P_L^{undesired} \end{cases} \tag{3}$$

The membership functions considered for reactive power transmission losses, $\mu_{QL}(Q_L)$ is similar to $\mu_{PL}(P_L)$.

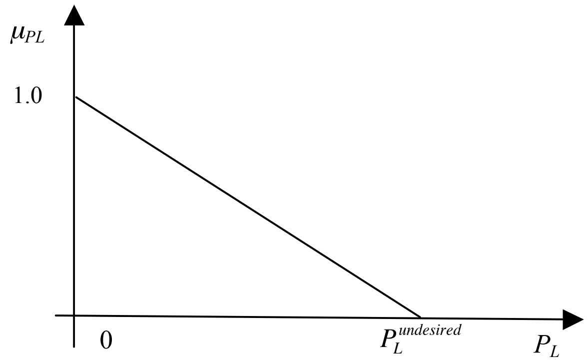

Fig. 2. The fuzzy membership function for the active power losses.

The constraints on transmission line flows are fuzzified using membership functions, which are similar to the membership functions used for the losses, and they are applied to all transmission lines in service. Here, the degree of satisfaction for the MVA flow is zero for any value of the MVA flow greater than the line's current carrying capacity limit. The system operators, who can take into account the feasible operating conditions, can determine the desired MVA flow limit of a specific line.

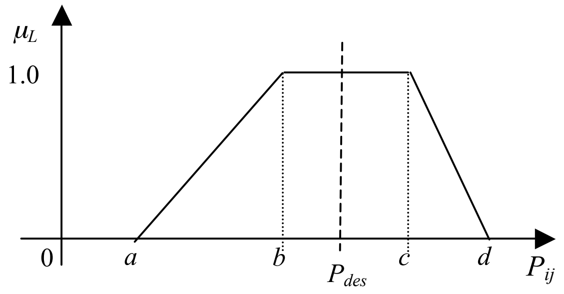

Fig. 3. The fuzzy membership function for the loop MW flows.

In this paper handling these flows as objectives in fuzzy environment performs the control of loop MW flows. The MW flows of the lines, where MW flow will be controlled, are fuzzified by membership functions in a trapezoidal form as shown in Fig. 3. They are described by four parameters (a,b,c,d) with four breakpoints of the trapezium. The membership function $\mu_{L,ij}(P_{ij})$ belongs to the MW flow through the line between bus i and bus j. The system operators taking into account the power flow contract paths can determine the four parameters of the function. The transmission charge has also an effect on the shape of the membership function.

The membership function $\mu_{L,ij}(P_{ij})$ is defined as

$$\mu_{L\,ij}(P_{ij}) = \begin{cases} \dfrac{P_{ij} - a_{ij}}{b_{ij} - a_{ij}} & if \quad a_{ij} < P_{ij} < b_{ij} \\ 1 & if \quad b_{ij} < P_{ij} < c_{ij} \\ \dfrac{d_{ij} - P_{ij}}{d_{ij} - c_{ij}} & if \quad c_{ij} < P_{ij} < d_{ij} \\ 0 & if \quad otherwise \end{cases} \tag{4}$$

where $a_{ij} < b_{ij} < c_{ij} < d_{ij}$ must hold.

The constraints on bus voltage magnitudes are fuzzified using membership functions described in trapezoidal form [11]. It can be seen from Fig. 4., that a bus voltage magnitude between desired values will have a satisfactory value of 1.0, and the membership value of $\mu_{c\text{-}V}(V)$ must be 0 if the constraints are strongly violated.

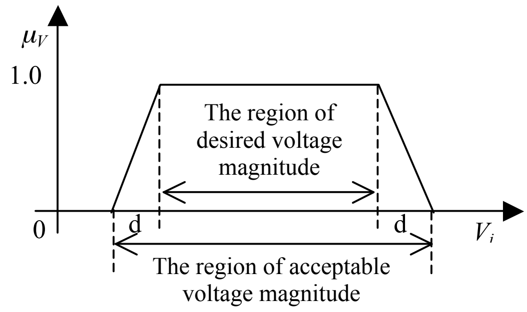

Fig. 4. Fuzzy membership function for bus voltage magnitudes.

The membership function for the bus voltage magnitudes, $\mu_{c-V}(V)$ is defined as

$$\mu_{c-V}(V) = \begin{cases} 0 & V < V_{\min} - d \\ \dfrac{V - (V_{\min} - d)}{d} & V_{\min} - d < V < V_{\min} \\ 1 & V_{\min} < V < V_{\max} \\ 1 - \dfrac{V - V_{\max}}{d} & V_{\max} < V < V_{\max} + d \\ 0 & V > V_{\max} + d \end{cases} \tag{5}$$

Calling the load flow program solves the equality constraints, which are the real and reactive power balances of the power system.

We represent the objective functions and the constraints in terms of fuzzy memberships functions $\mu_g(x)$ and the $\mu_c(x)$ respectively. We then try to obtain the most satisfactory conditions for a system operator. The higher the value of membership function the better is the satisfaction. Genetic algorithm (GA) is utilized to solve this fuzzy optimization problem. The proposed optimization procedure is given in Fig. 5.

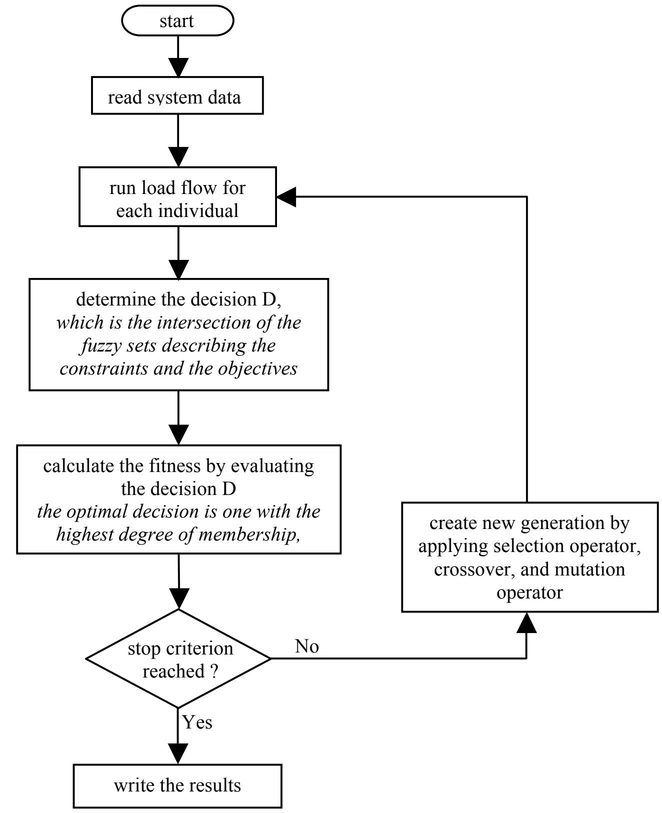

Fig. 5. Flow chart of the optimization procedure.

VI. SIMULATION RESULTS

The proposed method is applied to two different systems: IEEE 14-bus and IEEE 30-bus test system. The detailed data can be found in literature. The simulations are performed in Matlab environment using Matlab-Genetic Algorithm Toolbox and Matpower open source power flow simulation program. In the simulations, for both systems d=0.005 (see Fig. 4.) is taken in fuzzification of the voltage magnitudes, $P_L^{unsatified}$ and $Q_L^{unsatified}$ are taken as 1.8 times of active and reactive power losses of base case respectively. The parameters b and c are taken as 1 MW less and 1 MW more than the scheduled flow, respectively. The upper and lower un-satisfaction flow limits for the contracted path (a and d of Fig. 3) are taken to be 3MW less and 3 MW more than the parameters b and c. For example, for the 80 MW scheduled flow, the four parameters (a, b, c, d) are set to (76, 79, 81, 84) respectively.

The parameter values used in GA solution are as follows: the population size is 50, the string length is 9, and maximum generation is 100. The tournament selection function is used and the tournament size is 2, elitcount is considered as 2, two-point crossover is preferred for solution, crossover fraction is 0.8, and Gaussian mutation function is used. These parameter values are found after several trials to give the best results in terms of accuracy. The program is run 20 times and the obtained average values are given in Table 1.

In IEEE 14 bus system, given in Fig. 6, the ring between neighboring buses 2, 3, and 4 is selected to demonstrate the proposed method. The line 2-3 is considered as the contracted path, and the scheduled flows are taken as 80MW and 90 MW. Simulations are performed for two cases: case 1 is the system with series capacitor in line 2-3 and case 2 is the system without series capacitor. The series capacitor is also considered as an additional control device and the limit for series compensation degree K_S is taken as 0.3. It can be seen from the Table 1 that, for both cases the flows are improved to the scheduled values. While controlling the flows, voltage profile is improved, and line flows are kept within the line limits.

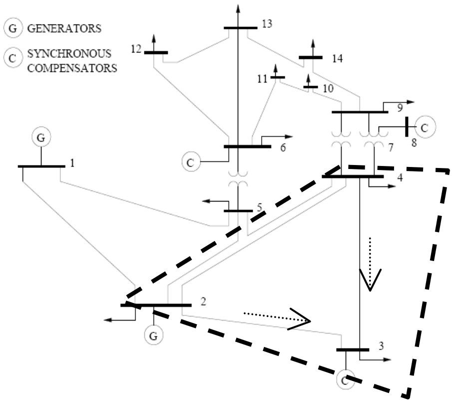

Fig. 6. IEEE 14-bus test system.

Let us consider a case in more detail. Assume we want to let flow of 80 MW on the contracted path, line 2-3. In the base case we have 73 MW flowing and we want to increase it to 80 MW. The losses are reduced 25% for 80 MW scheduled flow. When the amount of scheduled flow through the contracted path is increased to 90 MW, a higher satisfaction cannot be obtained with the existing system control devices, and the upper and lower unsatisfaction limits of the flow for the contracted path (a, d) need be relaxed. This is expected since the test case has only two generators, one of which is a slack bus. Thus, the number of controllable variables is not adequate. With series capacitor (SC) installed in line 2-3, the more satisfactory results are obtained. Changing the system operating conditions via the control devices compensates the negative effects caused by unscheduled flows. Applying the proposed method, the unscheduled flow through the line 4-3 is reduced from 23.66 MW to 9.13 MW. According to the results, the series compensation helps to increase the satisfaction degree.

Table 1. The results for IEEE 14-bus test system.

	Base Case	Scheduled flow			
		80 MW		90 MW	
		Without SC	With SC	Without SC	With SC
Line 2-3 MW Flow	73.24	78.44	79.10	83.04	88.93
Line 4-3 MW Flow	23.66	18.49	17.74	16.29	9.13
Ploss MW	13.39	10.11	10.963	20.953	11.558
Qloss MVAr	54.54	43.14	45.24	83.73	46.52
Satisfaction		0.44	0.66	0.13	0.64

Figure 7 shows the variation of the fitness value with respect to generation numbers for the study case, which is the 80 MW scheduled flow without SC for IEEE 14 bus test system.

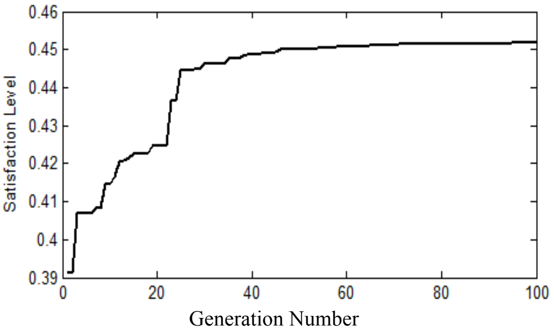

Fig. 7. Satisfaction level (degree of membership) with respect to number of generations for IEEE 14-bus test system.

The simulations are also performed on a modified IEEE 30 bus system. Modification refers to converting bus 5 into a generator bus. In this system, buses 1,2 and 5 are taken as the generator buses, and line 2-4 is considered as a contracted path for the flow control, and it is shown with dashed arrow in Fig. 8. As an example case, a scheduled power flow value is considered as 50 MW for line 2-4. The satisfactory solution for this test system is also obtained by using the proposed method as shown in Table 2 for two system cases: the system with series capacitor in line 2-4 and the system without series capacitor.

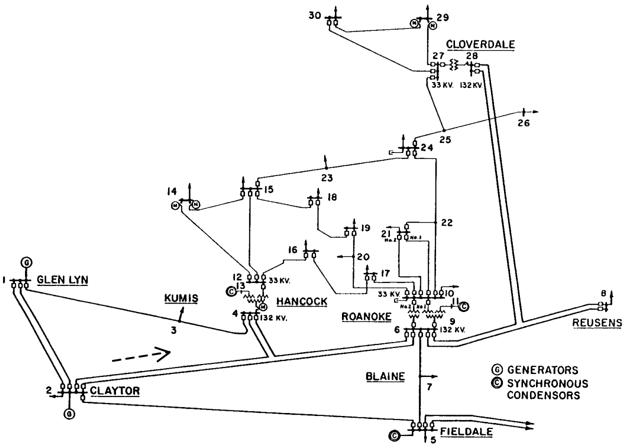

Fig. 8. IEEE 30-bus test system.

Table 2. The results for IEEE 30-bus test system.

	Base Case	Scheduled flow: 50 MW	
		Without SC	With SC
Line 2-4 MW Flow	41.86	48.65	51.03
Ploss MW	7.999	7.70	6.01
Qloss MVAr	35.06	34.64	26.74
Satisfaction		0.30	0.46

VII. CONCLUSIONS

A fuzzy set theory based genetic algorithm is proposed to control and/or prevent loop flow. In the method, as in practical cases, we allow small violations of the limits of the power system variables.

As seen from the Tables 1 and 2 without compensation, satisfaction levels are low for especially higher contracted flows, which is expected due to fewer numbers of variables to control. Flow level is far from the target level compared to that of the compensation case. With the additional control devices such as the series capacitors, we get the flow level closer to the target flow level and the satisfaction level also gets better, see Table 2. Reactive power losses are also decreased.

It is also observed that the slope of the membership function affects the satisfaction level appreciably.

When the classical methods are used to control loop flow in a rigid manner a feasible solution may not be found. However, using the proposed method one can find a feasible solution. This can be better adjusted using different membership functions.

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