Iranian Journal of Science & Technology, Transaction B: Engineering, Vol. 33, No. B6, pp 463-476
Printed in The Islamic Republic of Iran, 2009

OPTIMAL ISLANDS DETERMINATION IN POWER SYSTEM RESTORATION*

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Abstract– In this paper, the effect of the islands number variation in the restoration process is investigated and a method to determine optimum island boundaries is presented. Also, the impact of Parallel Reactive Power Sources (PRPS) on the number and boundaries of each island and restoration process is studied. In the optimization process, the objective function is minimizing Energy Not Supplied (ENS) and constraints are voltage margins in buses, transmission lines capacities and generators loading limits. The ENS is evaluated based on generation capacity allocation to demand loads method. Genetic algorithm (GA) is the base of optimization and an appropriate chromosome coding is developed for the network modeling. In order to assess the capabilities of the proposed method, the IEEE-118 bus network has been used as the test system. The results of sectionalizing the test system to 2 to 7 islands with optimum boundaries have been given in case studies.

Keywords– Genetic algorithm, graph theory, island, power system restoration, Parallel Reactive Power Sources (PRPS)

1. INTRODUCTION

The problems of failed system recovery to normal state are studied in power system restoration process topics [1, 2]. Power system restoration has been converted to a complex problem because of its versatility, nonlinear behavior and the relationship between its various elements. Various methods in power system restoration with the goal of recovery of the system to its normal operation state and supplying maximum loads have been proposed. These include mathematical programming [3], soft computing [4], heuristics methods [5, 6] and expert systems [3, 7, 8].

The restoration process has three main stages: generator units restarting, network restoration and load restoration [9, 10]. In order to have easy and fast execution of the restoration process, it is necessary to plan restoration strategies. The main goal of restoration planning and its implementation is to supply maximum load demand during restoration. In other words, achieving maximum load restoration in minimum time while all operation constraints have been satisfied. So far, various restoration strategies have been proposed which can be classified into the following general strategies:

1) The build down strategy
2) The build up strategy

In the first strategy, the main transmission network is restored in the beginning, then loads are reconnected step by step, the generator units are included in the network, consequently the restoration process will be in series form. The main shortcoming of this strategy is excessive reactive power, which is produced by light loaded connected transmission lines. Consequently, the use of this strategy is restricted

*Received by the editors April 7, 2007; Accepted September 29, 2009.
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to small-scale power systems with short lines or to power systems with high reactive power absorbing capability. The second strategy, which is the most practical method of restoration, is used in complete blackout condition where it is not possible to be supplied from adjacent power systems. In this method, the power system is sectionalized to some islands in the beginning of the restoration process. In each island, the existence of at least one black-start generator is necessary. Then the lines, loads and generators of each island are restored and finally, all islands are resynchronized together and the rest of the components are reconnected to the network [9, 11, 12]. The use of these methods depends on various factors, the range of outages, capability of adjacent systems support, load value and the number of black-start generator units.

As mentioned, one of the most important steps of the build up strategy is sectionalizing the network to some islands. Island formation in the initial stages of the restoration process as a step, is used for convenient restoration processes execution, increase of controllability of network, significant reduction of restoration duration, and finally, maximizing the supplied load in each instant of restoration so that all of them can be shown in the Energy Not Supplied (ENS) index.

Various factors influence the determination of the number of islands and their boundaries such as system operation point, network topology, existence of protection equipment, the number of restoration execution teams and even system dynamic considerations. To select the number and boundaries of the islands and group them, it is necessary to consider the following criteria [1, 5]:

I) Each island must have black-start capability, which is sufficient restarting critical equipment from off state.
II) Each island should have efficient generation capability to match demand load within predefined frequency limits.
III) Each island should have adequate voltage controls to maintain suitable voltage profile.
IV) Each island should be capable of being sufficiently monitored at the system control center in order to ensure its internal security and coordinate switching
V) Each island should have the ability of power transaction with other adjacent islands.
VI) Each island should have the capability of telecommunication with adjacent islands or with all islands.
VII) Synchronizing equipment should exist in the tie lines between islands.

It seems that the number of islands to be formed in the initial stages of the restoration process is predefined and island selection is accomplished according to the restoration engineer’s experience and there is no analytical basis for it [13, 14]. In many power systems, provincial boundaries, utility managing partitions and the power transactions between them have a vital role in an island’s number and their boundaries determination. However, selection of the number of islands must be done in a logical manner. Irregular increase of the number of islands, even with satisfying the conditions of island formation, may prolong the restoration time because of excessive synchronization operation and restoration team restrictions. It is obvious that if we determine the number and boundaries of islands optimally, it can lead to many desired advantages, as follows:

I) May cause reduction restoration process tasks and facility of its execution.
II) Dynamic conditions improvement in various stages of islands restoration and their resynchronization.
III) Speed up the restoration process and significant reduction of restoration time.
IV) Cost reduction and minimization of Energy Not Supplied (ENS) index.

This paper studies the impacts of the changing number and boundaries of islands in the restoration process and presents a method for the evaluation of optimal boundaries of islands. Also, it assesses the effects of installed PRPS in restoration process improvement. Optimization method is based on GA with an appropriate coding. For case studies, IEEE-118 bus [15] network is selected as the test system.

The paper is organized as follows: first, the network modelling and chromosome coding is presented; second, optimization method based on GA is proposed; third, the various test results of optimal sectionalizing of the test network to 2 to 7 islands with and without PRPS are presented and discussed; finally, the conclusions and references are presented.

2. NETWORK MODELLING AND CHROMOSOME CODING

In this section, chromosome coding in genetic algorithm optimization is introduced. First, a single line diagram of the network is substituted with the corresponding graph network. Then, the graph diagram of the network is traced and a code is assigned to each node showing the corresponding island number. Based on this number, chromosome coding is defined as shown in Fig. 1. Therefore, each chromosome code (or gene) is an integer number from 1 to existing maximum island number. For better illustration, chromosome coding for a 10-bus network (as shown in Fig. 2) with 2 islands is presented, Fig. 3 shows its graph network. As it is observed, the nodes 1, 4, 5 and 9 lie in island 1 and also nodes 2, 3, 6, 7, 8 and 10 lie in island 2. The chromosome coding that shows this state will be 1221122212. Also, Fig. 4 shows the corresponding network graph with 3 islands. As seen, the nodes 1, 2 and 4 have been laid in island 1, nodes 3, 7 and 8 in island 2 and nodes 5, 6, 9 and 10 in island 3. The chromosome, which shows the above islands arrangement, will be 1121332233.

Node 1	**Node 2**	**…**	**Node i**	**…**	**Node N**
b1	b2		*bi		bn

* If Node i is in k^{th} island, then bi=k.

Fig. 1. Chromosome structure and coding

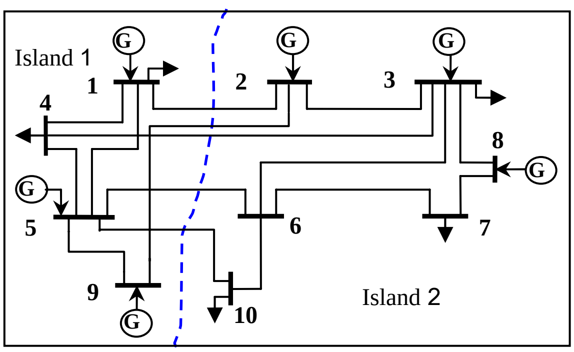

Fig. 2. Single line diagram of a 10-bus network

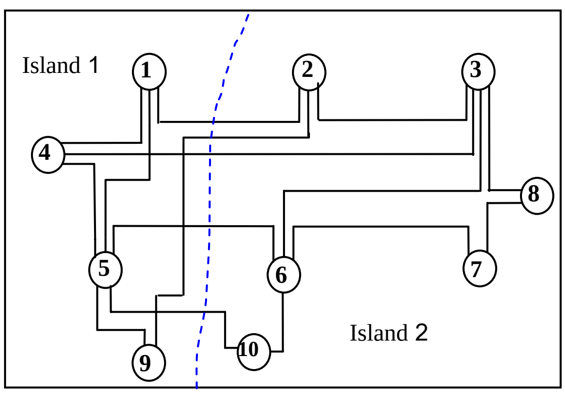

Fig. 3. Equivalent graph of Fig. 2

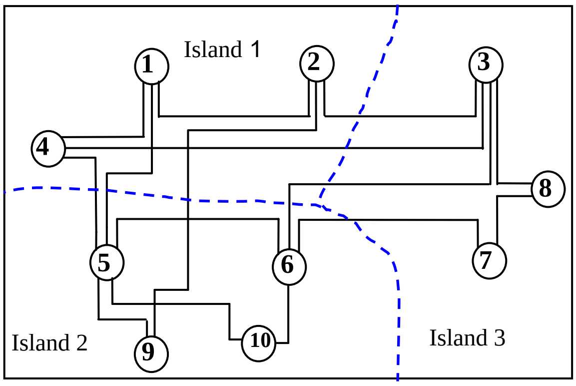

Fig. 4. Graph of a 10-bus network with 3 islands

3. THE PROPOSED GA BASED ALGORITHM STEPS

The proposed algorithm for sectionalizing the network to some islands and evaluating their optimum boundaries has the following steps:

I) Initial Population Generation: Initial population of chromosomes is generated randomly. Genes in each chromosome are random numbers from 1 to maximum islands number.

II) Islands determination: With chromosome decoding, buses for each island are determined.

III) Black-start units existence condition: The condition of existence of at least one black-start unit in each island is checked. If this condition is not satisfied even in one island, the corresponding chromosome will be rejected from the optimization process.

IV) Connectivity condition: The connectivity of nodes in an island using coding of generated chromosome is assessed. For instance, for the network shown in Fig. 2, chromosome 1211221122 that partitions the system to 2 islands, is rejected because of non-connectivity of the internal graph of the related island 1.

V) Load flow calculation in each island: In this step, load flow study is done in each island while tie lines with other islands are out of system in order to check operation constraints. Variables that will be checked in this step with their constraints are: voltage at buses and transmission lines and generators loading. Even if only one of the above constraints is violated, the corresponding chromosome will be rejected and only chromosomes which satisfy all mentioned constraints will cooperate in the optimization process.

VI) Allocation of generation to loads and ENS evaluation: In this step, by a special mechanism as shown in the flowchart in Fig. 5, the generation capacity in each island will be allocated to loads. After determination of the necessary time for loads to connect to generators, ENS is evaluated. Also, load priority and its importance in the restoration process using weighting factors can be considered. In each step of generation allocation to demand loads, all transmission lines path sections that must be switched will be recorded. Also, predefined time duration is applied for switching time considerations. With the load supplying progress, step by step reduction of not supplied loads, and regarding switching time amount, the approximated value of ENS index can be evaluated.

VII) Selection: After evaluation of ENS for each chromosome**,** their ranking is done based on fitness value that is ENS value inverse as (1). Some chromosomes are selected for participation in the optimization process which have higher fitness values.

$$Fitness \quad Fun. = \frac{1}{ENS} \tag{1}$$

VIII) Crossover and Mutation operators: Iterative optimization process is performed in selected chromosomes with various genetic operations containing crossover and mutation to improve results and achieve a final solution.

Convergence checking: In the final step, if the results have converged to maximum fitness value or minimum ENS in islands, the optimization process is finished. It is obvious that, in the optimal final solution, each island and its boundary is determined. In each island, generation can match demand loads and it is expected that the transmitted power of the tie lines be at minimum levels.

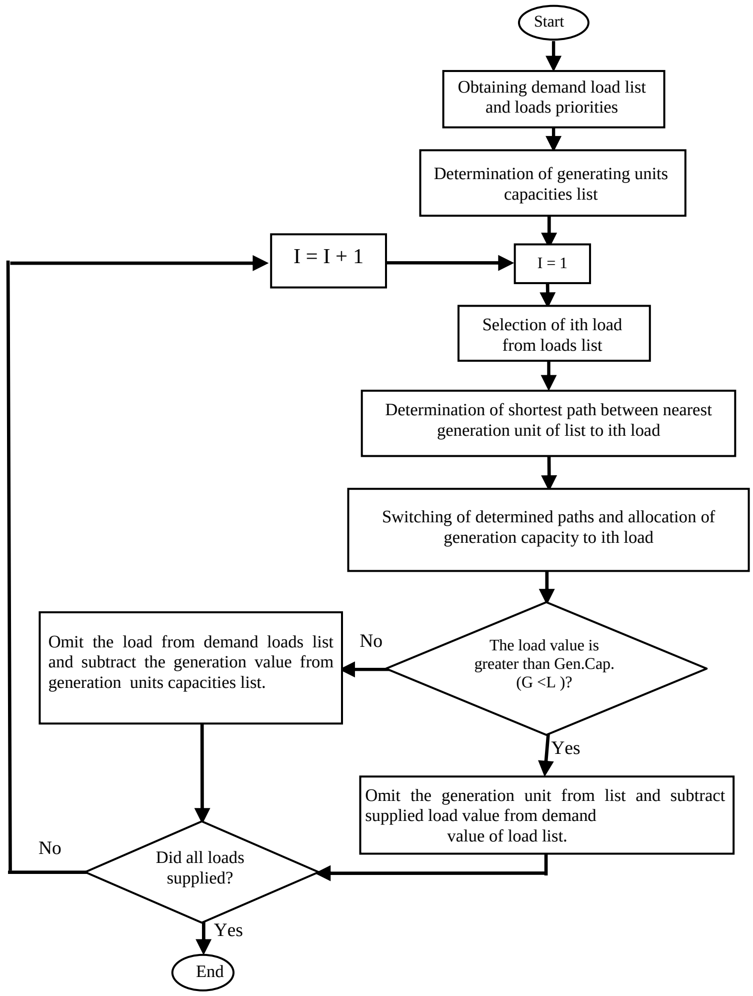

Fig. 5. Flowchart of generation capacity allocation to demand loads

4. PARALLEL REACTIVE POWER SOURCES (PRPS) MODELLING

Parallel Reactive Power Sources (PRPS) existence in a network can affect power system operation [16]. These reactive sources such as static var compensator (SVC), STATCOM are connected in parallel with buses and inject defined values of reactive power to the network. Figure 6 shows electric circuit equivalent of a SVC as a PRPS which contains parallel capacitance banks (C), a set of shunt reactors (L) and fast controlling thyristor switches [17,18]. Thyristor firing angle controlling will change the total reactance value of SVC from –XC to XL. Then the injected reactive power of SVC can change continuously.

PRPS can also improve the restoration process. This work is done by modifying the voltage profile of buses, which may have under or over voltage in restoration process progress. On the other hand, PRPS can improve over loading of some transmission lines with displacement loads of other lines.

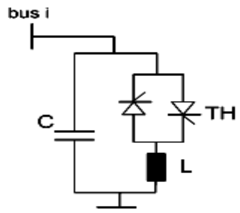

Fig. 6. Static Var Compensator (SVC) circuit

So far, various PRPS models have been proposed that can be divided into general passive and active categories. In the passive case, PRPS is modelled as variable impedance, which permanently controls the voltage level. In the active model, PRPS injects reactive power to connected buses to control the voltage level. In this paper, according to the active model, PRPS is considered as a PV bus with zero active power (P=0) which permanently controls the related buses voltage level. It is necessary to remember that we will use only capabilities of the existing PRPS which have been installed in the network for operation objectives and no new PRPS is installed for restoration process execution and implementation.

5. CASE STUDIES

In order to assess the capabilities of the proposed method, the IEEE-118 bus is selected as the test system. Regarding the total number of the test system buses, each chromosome code is a 118-digit integer number. Case studies have two sections. In the first section, the test system is sectionalized to 2 to 7 islands based on the proposed method in absence of PRPS. In the second section, the test system is sectionalized to 2 to 7 islands in presence of PRPS**.** Each population generation has 50 chromosomes which participate in the optimization process. The optimization iterations will stop if the obtained objective function converges to a constant value and does not have any variations.

a) Cases studies in IEEE-118 bus test system without PRPS

1. Sectionalizing the test system to 2 islands: In this case, the test system is sectionalized to 2 islands using a particular coding of chromosomes. The final optimum boundaries of each island are determined using genetic algorithm. Table 1 and Fig. 7 show the final chromosomes and optimum boundaries of each island, respectively. The results of generation capacity allocation to demand loads in a time sequence mechanism for island 1 has been given in Fig. 8.

To include dynamic consideration of switching operations in the program, the switching time is assumed to be 120 seconds and then the minimum ENS index will be obtained. Figure 9 shows the values of this index for each island and total network. All operation constraints contain buses voltages, lines flow, and generators active and reactive powers are in rated allowable ranges too.

Table 1. Final chromosome arrangement and island buses of the test system with 2 islands without PRPS presence case

Test system with 2 islands without PRPS presence case	**Chromo-some**	1111111111111111111122222122212211111111111222211111111111111111111222222222222222222… 222222222222222222222222222122212
	IS1 Buses	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,26,30,33,34,35,36,37,38,39,40,41,42,43,48,49,50,51,52, 53,54,55, 56, 57,58,59,60,61,62,63,64,65,66,67,113,117
	IS2 Buses	1,22,23,24,25,27,28,29,31,32,44,45,46,47,68,69,70,71,72,73,74,75,76,77,78,79,80,81,82,83,84,85,86,87,88, 89,90,91,92,93,94,95,96,97,98,99,100,101,102,103,104,105,106, 107,108,109,110,111,112,114,115,116,118

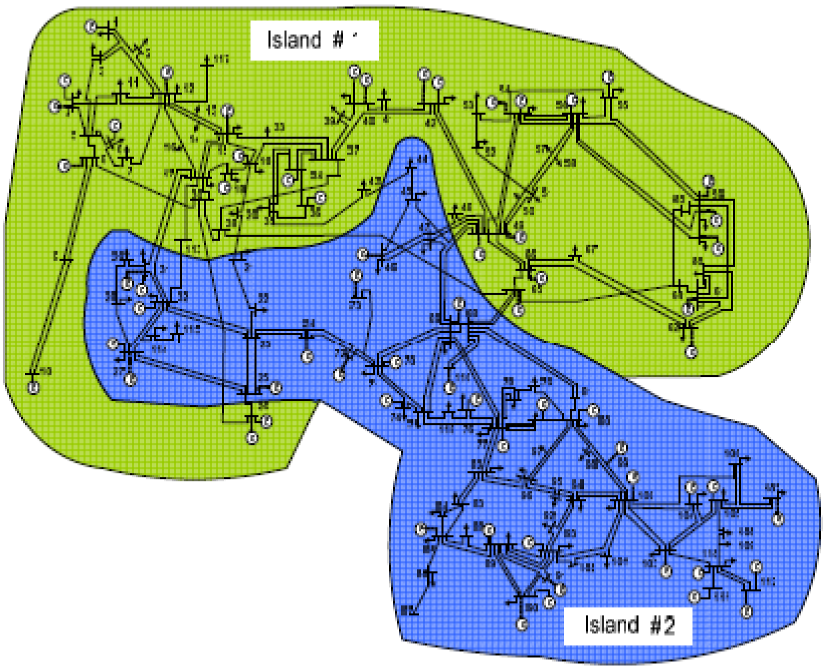

Fig. 7. Test system with 2 islands without PRPS presence case according to Table 1

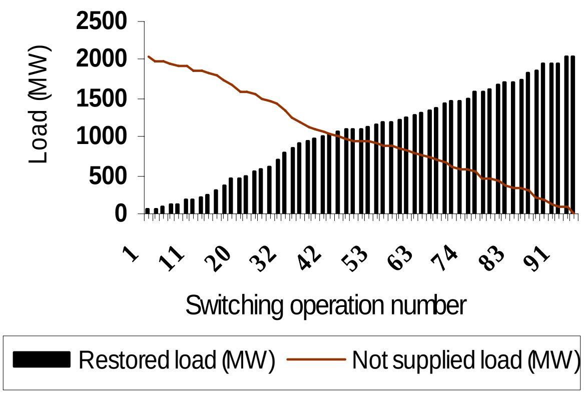

Fig. 8. Generation capacity allocation to loads of island 1 without PRPS case

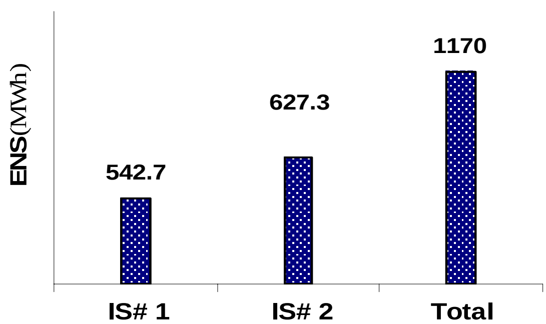

Fig. 9. ENS values of islands 1, 2 and total ENS of the test system without PRPS case

2. Sectionalizing the test system to 3 islands: In this case, the chromosome code is a 118-digit integer number containing numbers 1, 2 and 3. After optimization, the final solutions of simulation including optimum chromosome arrangement and boundaries are represented in Table 2 and Fig. 10, respectively. After applying 120 seconds as switching time, Fig. 11 shows the ENS of all three islands and total values.

3. Sectionalizing the test system to 4, 5, 6 and 7 islands: In this case, the test system is sectionalized to 4 to 7 islands without PRPS presence condition. The final chromosome arrangement has been given in Table 3. Each island bus numbers can be easily determined from the related chromosome arrangement. Also in Table 4, ENS for all mentioned cases is shown.

Table 2. Final chromosome arrangement and islands buses of the test system with 3 islands without PRPS presence case

Test system with 3 islands without PRPS presence case	Chromo -some	11111111111111111111111311111111111111133313333333333333333333333333333333222223222… 2222222222222222222222222222222111313
	IS1 Buses	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,25,26,27,28,29,30,31,32,33,34,35,36,37,38,39, 43,113,114,115,117
	IS2 Buses	76,77,78,79,80,82,83,84,85,86,87,88,89,90,91,92,93,94,95,96,97,98,99,100,101,102,103,104,105,106,107, 108,109,110,111,112
	IS3 Buses	24,40,41,42,44,45,46,47,48,49,50,51,52,53,54,55,56,57,58,59,60,61,62,63,64,65,66,67,68,69,70,71,72,73, 74,75,81,116,118

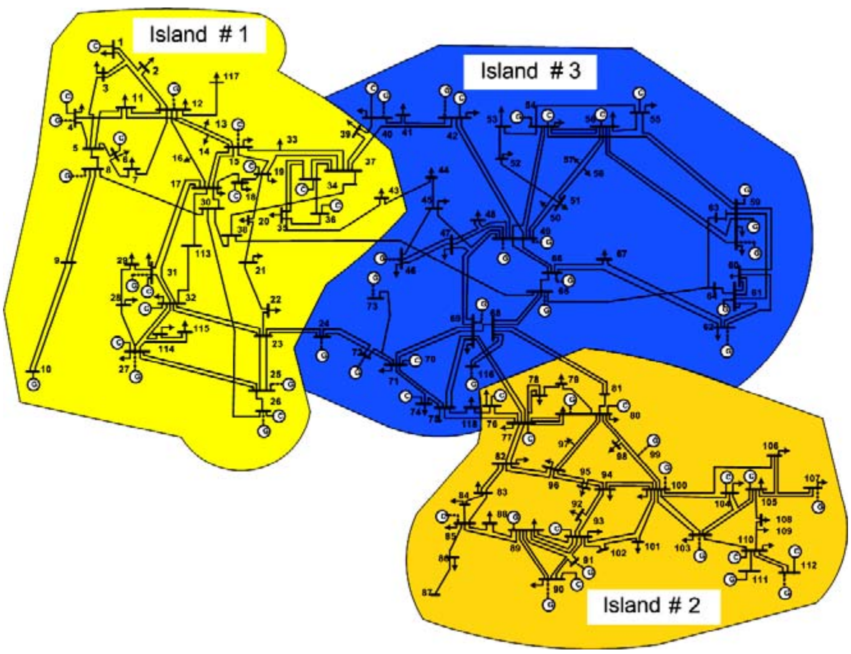

Fig. 10. Sectionalizing of the test network to 3 islands without PRPS presence case according to Table 2

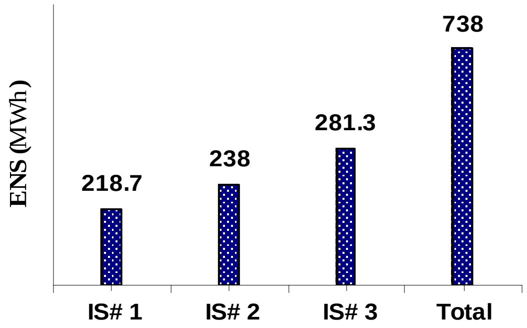

Fig. 11. ENS values of islands 1, 2, 3 and total ENS of the test system without PRPS case

Table 3. Final chromosome arrangements of sectionalizing test system to 4, 5, 6 and 7 islands without PRPS presence cases

Test system with 4 islands	111111111111111111244444411111141222111122222222222222224222422224442244444444444444433333… 3333333333434333333333333333111414
Test system with 5 islands	111111111111121111222252222121222222222222222232333333333333332223355555555555555555555… 444444444555444444444444444122515
Test system with 6 islands	111111111111111111332222221222122133331333333336344444444444444441446662226666666666 6666… 55555555565555555555555555122616
Test system with 7 islands	111111111111111111332222221222122133331333433335344444444445554555445555255577777577777… 76666667776766666666666666222515

Table 4. ENS values of each island and total ENS in cases of the test system with 4 to 7 islands without PRPS presence conditions

ENS (MWh) / Cases	ENS (IS1)	ENS (IS2)	ENS (IS3)	ENS (IS4)	ENS (IS5)	ENS (IS6)	ENS (IS7)	ENS (Total)
Test system with 4 islands	126	134	121	144	---	---	---	525
Test system with 5 islands	64	88.6	78	71	111.3	---	---	412.9
Test system with 6 islands	52.9	26.4	32	70.5	85.6	90.3	---	357.7
Test system with 7 islands	53	25.8	24.5	40	29.9	51	60.5	284.7

b) Case studies in IEEE-118 bus test system with PRPS

1. Sectionalizing the test system to 2 islands: In this case, the test system is sectionalized to 2 islands with four existing PRPS which have been installed in buses 22, 38, 53, and 96 according to Table 5. Then, the islands optimum boundaries are determined using genetic algorithm optimization method with minimum ENS objective function. Table 6 shows the final chromosomes arrangement and the bus numbers of each island. Figure 12 shows the final single line circuit of the test network. Figure 13 also shows the ENS index in the above stated case. All operation constraints contain bus voltages, line flows and generators, active and reactive powers are in rated allowable ranges too.

Table 5. Data of four existing PRPS installed in the test system

No	Bus	Mvar_min	Mvar_max
1	22	-50	+80
2	38	-50	+125
3	53	-50	+100
4	96	-50	+120

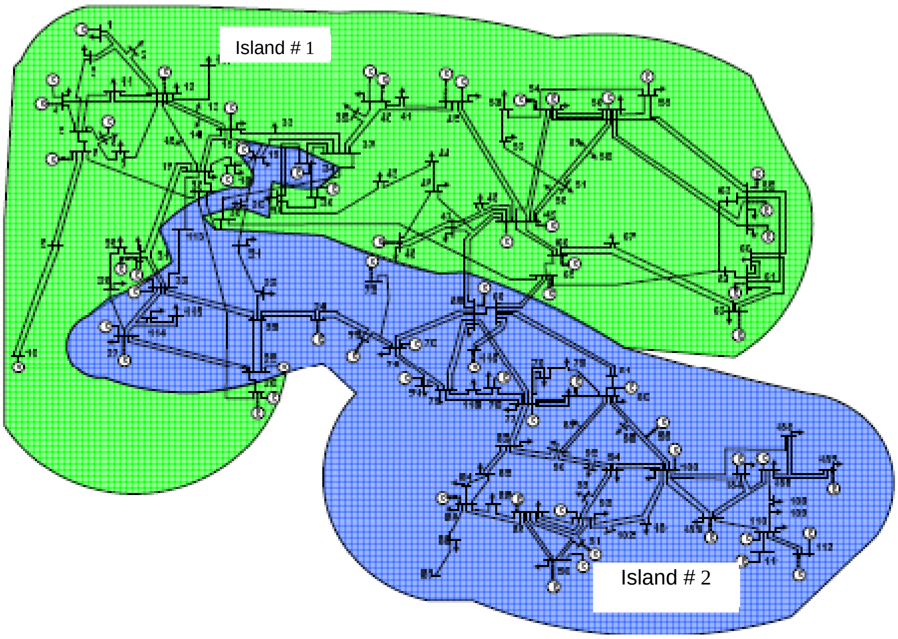

Fig. 12. Test system with 2 islands in PRPS presence case according to Table 6

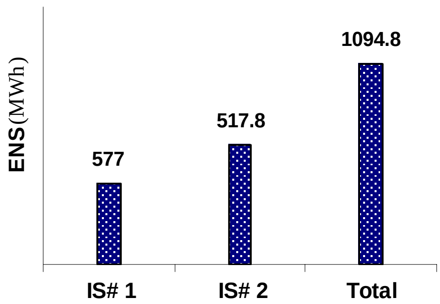

Fig. 13. ENS values of islands 1, 2 and total ENS of the test system in PRPS presence case

2. Sectionalizing the test system to 3 islands: In this case, like section 5.1.2, the test network is sectionalized to 3 islands in the PRPS presence condition. Chromosome code is a 118-digit integer number that contains numbers 1, 2 and 3. Table 7 shows the optimum chromosome arrangement and the boundaries of sectionalizing the test system to 3 islands in PRPS presence cases. Bus numbers of each island can be also determined from the chromosome arrangement. Figure 14 shows the test system with 3 islands in the PRPS presence case. Also, ENS values of each island and total ENS in the case of sectionalizing the test system to 3 islands in PRPS presence has been given in Fig. 15.

Table 6. Final chromosome arrangement and island buses of the test system with 2 islands in PRPS presence case

Test system ith 2 islands in PRPS presence case	**Chromo-some**	111111111111111111222222212111121211111111111111111111111111111111111122222222222222… 22222222222222222222222222222222222212
	IS1 Buses	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,26,28,29,30, 31,33,35,36,37,38,39,40,41,42,43,44,45,46, 47,48,49,50,51,52,53,54,55,56,57,58,59,60,61,62,63,64,65,66,67,117
	IS2 Buses	19,20,21,22,23,24,25,27,32,34,68,69,70,71,72,73,74,75,76,77,78,79,80,81,82,83,84,85,86,87,88,89,90, 91,92,93,94,95,96,97,98,99,100,101,102,103,104,105,106,107,108,109,110, 111,112,113,114,115, 116,118

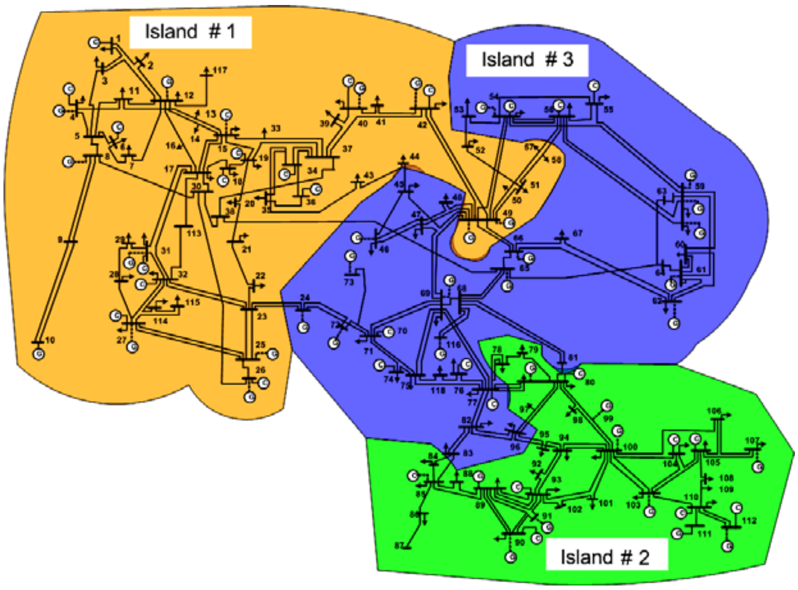

Fig. 14. Sectionalizing of the test network to 3 islands
in PRPS presence case according to Table 7

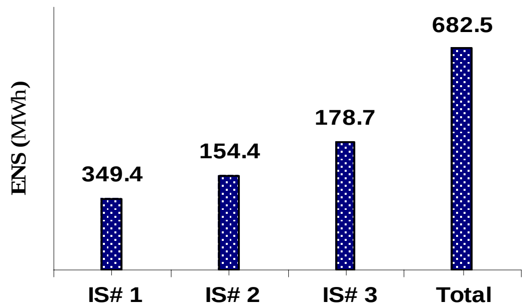

Fig. 15. ENS values of islands 1, 2, 3 and total ENS of the
test system in PRPS presence case

Table 7. Final chromosome arrangement and island buses of the test system
with 3 islands in PRPS presence case

Test system with 3 islands in PRPS presence case	Chromo-some	1111111111111111111111113111111111111111111111333311113333113333333333333333333322233… 3222222222222232222222222222222222111313
	IS1 Buses	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,25,26,27,28,29,30, 31,32,33,34,35,36,37,38, 39,40,41,42,43,44,49,50,51,52,57,58,113,114,115,117
	IS2 Buses	78,79,80,84,85,86,87,88,89,90,91,92,93,94,95,97,,98,99,100,101,102,103,104,105,106,107,108,109,110, 111,112
	IS3 Buses	24,45,46,47,48,53,54,55,56,59,60,61,62,63,64,65,66,67,68,69,70,71,72,73,74,75,76,77,81,82,83,96,116, 118

Table 8. Final chromosome arrangements of sectionalizing test system to
4, 5, 6 and 7 islands in PRPS presence cases

Test system with 4 islands	1111111111111111112244444111111412121112222222222222224442242224442244444444444444… 333333333333333443333333333333111414
Test system with 5 islands	11111111111121111122252222121222222222222222232333333333333233223355555555555555555… 55 5444444444445444444444444222515

Test system with 6 islands	111111111111113113333322112221223333313334333364444444664464446664466222226666666… 6666665555555555555565555555555555122616
Test system with 7 islands	11111111111111212332222221222122233331333433335344444445445554555445555255555577757… 7777766666777777666666666666666222515

Table 9. ENS values of each island and total ENS in cases of the test system with 4 to 7 islands in PRPS presence conditions

Cases \ ENS (MWh)	ENS (IS1)	ENS (IS2)	ENS (IS3)	ENS (IS4)	ENS (IS5)	ENS (IS6)	ENS (IS7)	ENS (Total)
Test system with 4 islands	123	96	107	170	---	---	---	496
Test system with 5 islands	62.3	80.2	78	83.5	91.8	---	---	399
Test system with 6 islands	33.7	23.6	58.3	40.8	82.5	95.2	---	334.1
Test system with 7 islands	32	40.5	24.5	29	49	44	41	260

3. Sectionalizing test system to 4, 5, 6 and 7 islands: In this step, optimization is done for sectionalizing the test system to 4 to 7 islands in PRPS presence cases in which some obtained results have been given here. Tables 8 and 9 show the final chromosome arrangement and related ENS values, respectively.

c) Case comparison

Figure 16 shows ENS values of sectionalizing the test system to 2 to 7 islands with and without PRPS. As shown in this figure, ENS is seriously decreased if the islands increase. Then, as the number of islands increase, the ENS reduction rate is decreased and then kept constant. After this, the increase in further islands may really have no effect in ENS index reduction. On the other hand, according to the obtained results, with the 4 existing PRPS, increasing islands will decrease the ENS index more severely than the cases of network having no PRPS. Therefore, increase of PRPS which have been installed in optimal locations can significantly improve restoration process execution. Also, as seen in Fig. 16, the ENS value of the sectionalizing test system to 5 islands in the PRPS presence case (ENS=399 MWh) is closer to this index value in the sectionalizing test system to 6 islands without PRPS case, (equal to 357.7 MWh). As another example, the ENS value of the test system with 7 islands without PRPS (ENS=284.7MWh) is close to the ENS value of the sectionalizing test system 6 islands with PRPS (equal to 334.1 MWh). Therefore, the existence of a sufficient number of PRPS with appropriate capacities can reduce the necessary island number in the initial stages of the restoration process without a significant increasing of ENS index that can, for the most part, change restoration strategies.

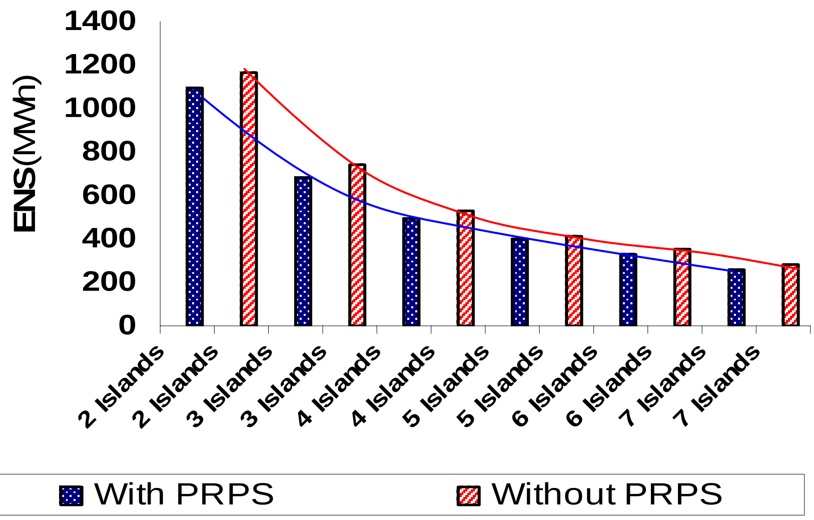

Fig. 16. Comparison of ENS values of network with 2 to 7 islands in PRPS presence and without PRPS cases

6. CONCLUSION

In this paper, the impact of changing the number and boundaries of islands on the restoration process has been studied and a method has been developed to determine the optimal boundaries of thee islands. Also, using the proposed method, the effects of PRPS in restoration process improvement have been investigated. Optimization method has been the genetic algorithm and the minimum ENS has been considered as an objective function. The IEEE-118 bus network has been used as the test system and the capabilities of the proposed program have been assessed using sectionalizing test system to 2, 3, 4, 5, 6 and 7 islands in PRPS presence and without PRPS cases. According to the obtained results, increasing islands from 2 to 3 will severely reduce the ENS index. This process is then constant and greater increase of further island numbers may have a negligible effect on ENS reduction. On the other hand, increasing islands in PRPS presence condition will reduce ENS value more severely than the case no PRPS existence. Therefore, using the capabilities of FACTS devices, the restoration process can be improved and ENS value can be significantly reduced.

LIST OF ABBREVIATIONS AND SYMBOLS

Acronyms:

ENS	energy not supplied
FACTS	flexible AC transmission systems
GA	genetic algorithm
PRPS	parallel reactive power sources
SVC	static var compensator
STATCOM	static compensator
TCR	thyristor controlled reactor
TH	thyristor

Acknowledgment: The corresponding author (M. R. Haghifam) would like to thank Prof. H.-J. Haubrich, head of the Institute of Power System and Power Economics (IAEW), and the Alexander von Humboldt Foundation for support of his research at IAEW, RWTH Aachen University, Aachen, Germany.

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