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Optimal Power Restoration in MV Distribution Network with Optimal Allocation of Remote Controlled Switches

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Abstract-This paper presents a heuristic programming approach of optimal restoration of Medium Voltage radial distribution network. After the isolation of the faulty section, the supplying must be restored in the whole area through the network reconfiguration. A new methodology to find remote controlled switches (RCS) optimal location in a Medium Voltage (MV) distribution network is presented. This methodology is based on the minimization of Energy Not Supplied (ENS) for the whole electric system, considering the possible switches locations in every feeder. This methodology considers also the normally closed (NC) and normally open (NO) switches previously installed in the MV network. Reliability data relating to power lines are necessary. The ENS cost for each load pointand total ENS is also considered. Finally, the proposed methodology can help a system operator to evaluate the economic impact of new RCS switches in a given distribution system.

Key Words-Energy Not Supplied (ENS), Remote Controlled Switches, Distribution Power System, Medium Voltage Network.

INTRODUCTION

When an outage occurs in a radial distribution MV network, breakers and protection relays disconnect the faulty area of thesystem. Some customers may thus be affected and disconnected, until repairing the faulty line and restoring the faulted area. To restore a maximum number of customers and limit the outageduration for them, it is possible to install RCS switches in the network, in order to operate a reconfiguration of the system. Simulated technique was employed to identify optimal placement of a limited number of RCS as well as the optimal sequence of operation. This simulation was carried out using dig-silent power factory(DSL) software.We find the best configuration and take into consideration electrical constraints such as line current capacities and voltage level. Defining the optimal location of RCSand also network reconfiguration after fault occurs requires a rigorous methodology to deal withcombinatory and probabilistic aspects. Various techniques, methods, and algorithms can be found in the literature.The electrical power systems are concerned with events that are at most unscheduled and associated with repair tasks due to equipment failures, weather, and collision [1]. The investment in [2] proposed a new formula for optimal number and placement of protection switches taking into consideration the cost of the devices and the maintenance. This formula depends on the simulated annealing technique.

After a fault occurs, fast detection of outages area and good planning for rapid restoration were envisioned in [3, 4] to build more reliable and secure power system. Distribution system restoration strategies to recover electric service in distribution network to the interrupted customers were presented in [5, 6].

Brown *et al.* [7]proposedan economics method to obtainan automated primary distribution system as well as design reliability and cost optimization dedicated to planning studies. A comparative analysis of several methods is presented. The approach represents the best method taking into consideration the cost and the reliability of the various power system devices. Teng and Lu [8] represent a heuristic method for feeder protection switches relocation for customer interruption, the objective being the minimization of the customer's interruption cost. Celli and Pilo [9] identify the optimal number and location of the switches in the MV networkusing a methodology based on the Bellmann optimization principle. The objective is to maximize the global benefit; the result of this algorithm determined the number of protection switches and their optimum location.Ramirez and Bernal [10] show a multi objective methodology to find the best distribution network configuration with the lowest cost by using an algorithm. The results of thisalgorithm provide the size and the optimal location of feeders. According to [11],Bouhouras*et al.* used an artificial intelligence technique with multiagent system for performing cost/worth assessment of reliability improvement in distribution networks.An approach presented in [12] isa statistics technique to minimize the outage time and restoration analysis in distribution systems. Reference [13] improves the reliability and reduces the cost of non supplied customers and shows the importance of automation in electrical distribution networks to run costs/benefits analysis of network automation. Reference [14] introduces the estimation of costs/benefitsusing concept of time varying failure and restoration times aftertaking into consideration the weather conditions impact on the restoration of the electric service. Allan and Silva [15] evaluate probability distribution associated with the reliability index of non radial networks. This approach is based on mixing analytic techniques and Monte Carlo simulations.

Some models and techniques are used for the optimization of global costs considering the cost of ENS losses as well as maintenance and investment costs in [16]. Reference [17] uses the Monte Carlo technique and considers the load variation for evaluatingthe unavailability costs of the customers in a distribution system.Reference [18] uses the mathematical equations for evaluatingthe Energy Not Supplied for every load points in a distribution system and total ENS.In [19–21], the methodology used remotecontrolled switches with minimum number to maximize the restoration capability and minimum switch upgrade cost. But single-fault conditions were only simulated.The restoration plan optimization problem is a nonlinear problem with power flow operation limits and topology constraints. Several researches were published to solve this problem with different approaches, using multiagent system [22], heuristic methods [23], expert system [24], neural network [25], fuzzy logic, ant colony, Tabu search [26,27], mathematical programming [28,29], and with microgrids [30].

This paper presents a methodology that allows optimum number and allocation of RCS switches in a benchmark MV model and real MV distribution network toenhance the reliability and ensure a minimum ENSwas obtained. The methodology is based upon the reliability data and consecutive installation of one pair of RCS switches in backbone feeder. All the possible location pairs are generated.Therefore, the selection always leads to the optimum choice, as all the options are evaluated. The method can be applied, for example, to estimate the economic advantageof investments by comparing the total annual cost, through the ENS and its initial value and taking into account voltage constraint alleviation and feeder should not be overloaded.

PROBLEM FORMULATION

Figure 1 illustrates the methodology employed to solve the optimization problem of power restoration as a multi objective function multi constraint. The method applied to find the optimum switching plan gives the optimum network reconfiguration which fulfills the objective functions of maximizing power restoration, minimizing the number of switching operations, and satisfying load balancing to minimize the overload risk andavoid violating constrains of voltage limits, feeders radiality, and feeder capacity limits.

The optimum power restoration algorithms are formulated as follows:

$$MinENS = \sum_i (\lambda_i * d_i * T_i * P_k * C_k)(1)$$

Let us consider the following statistical index:

i load point,

λ_i Failure rate (time/Km/year),

d_i Length of the line (Km),

T_i Repair time (hour),

P_k Active power (KW),

C_k ENS cost ($/KWh).

$$\text{Min (sw)} = \sum_{i=1}^{N} |SWi - SWRi| \quad (2)$$

N the number of switches in the network.

SW_i the status of i^{th} switch in network after fault.

SWR_i the status of i^{th} switch in the network after restoration.

The constraints are

1- Network radiality structure.

2- Feeders which should not be overloaded.

$$I \leq Imax, \quad (3)$$

3-bus voltages which should not violate their limits.

$$|V\ min| \leq |Vj| \leq |V\ max| \quad (4)$$

The proposed method applied for the optimum allocation of RCS in the restoration process is summarized by the flowchart in **Figure1**.

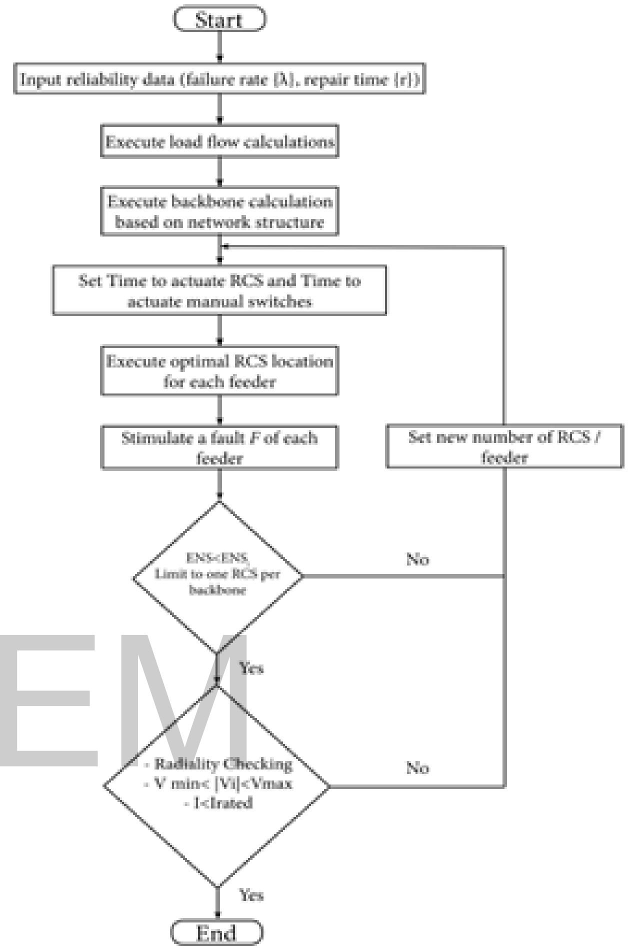

Figure1: Flowchart of the proposed DSL.

The program methodology makes an ENS value corresponding to the initial ENS of the MV network. The program methodology can be described by the following steps:

Defining the network elements (topology, feeders, loads, cables, switches type, switches location, lines unavailability, line length, failure rates, repair times, switches actuate times, load active powers, and ENS costs).

1. Initial calculations of the load flow, the reliability, and the ENS of the system.

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2. Defining the main feeder numbers and their path.
3. Executing all recommended locations of RCS, one/each feeder.
4. Executing reliability calculation for each scenario.
5. Executing optimal power restoration for each scenario.
6. Selection of the best options of locations (based on the minimum ENS).
7. Verification of the electrical constraints.
8. Outputting results data file, which shows the optimum locations found and the associated ENS with everyone.

CASE STUDIES

Benchmark Test

Figure 2 shows a simple test network ofbenchmark MV radial distribution network developed in DSL. The network is made of ten lines where two feeders and six loads are separated by three tie-open points. In a typical scheme there is always a circuit breaker in the beginning of every feeder, associated with a relaying device. Reliability parameter has been defined for each element.The methodology illustrates the impact of installation of single RCS in each feeder to minimize the ENS.

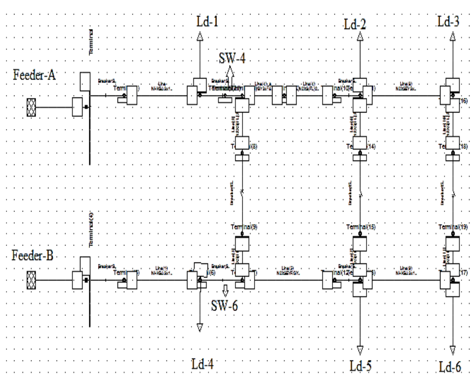

Figure2: Benchmark MV radial distribution network.

TABLE-1

Results optimal RCS placement in benchmark MV radial distribution network

Calculation of optimal RCS	for all feeders
placement:	on backbones of
Determination of optimal	feeder simultaneously
RCS positions:	Minimize ENS
Objective function for	Fix number of new
Optimization:	RCS
Method for number of RCS:	1
Number of new RCS per	all backbones of
feeder/backbone:	feeder
Backbones for RCS	1.00 min.
placement:	30.00 min.
Time to actuate RCS:	
Time to actuate manual	
switches:	
Calculation results of	FD_01
optimal RCS placement	
Feeder:	FD_01_FD_1 (1)
Backbones:	FD_01_FD_21
Number of new RCS per	6.046 MWh/a
feeder:	SW_04
Expected ENS:	FD_02
Optimal RCS:	FD_02_FD_1 (1)
Feeder:	FD_02_FD_21
Backbones:	3.712 MWh/a
Number of new RCS per	SW_06
feeder:	
Expected ENS:	
Optimal RCS:	

The output result calculation is recommending install two remote control switches at locations “Switch4" and “Switch6" to minimize the ENS. By running the reliability assessment for figure 1 in different cases. The base case chosen for the radial network is a standard case as DSL; case 1 is same as base case without RCS installed and case 2 using the mentioned recommended switches to be remote controlled type with actuating time 1 min.

Table 2 shows an ENS of 24.705MWh/a ofCase 1. Compared to the 22.214 MWh/a ENS in the base case [20] which is demonstrated in the reference simulation, this result is more than what it should be. This is because variable load was not implemented. But the value of ENS in Case 2 after installing RCS shows the significant improvement of reliability indices after applying the proposed method. Since this is a simple example in principle, we can get and estimate the plausibility of the proposed method. As has been mentioned in **Table 2**, the benchmark test responds to reduction of ENS and interruption cost by installing 1 pair of RCS.

Table-2
Results of reliability summary for benchmark test.

	No of RCS	SW "ID"	Action	Reason	ENS (MWh/a)	Interruption cost (k$)
Case1	-	-	-	-	24.7	18
Case2	2	SW_4 SW_6	Open Close	-Clear fault. -Power restoration.	3.71	2.3

Figure 3 represents the voltage profile of the 10 feeders during normal operation and after fault isolation at Section 2

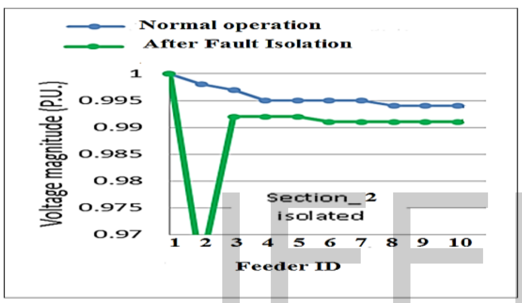

Figure 3: Voltage profile of feeders during normal operation and after fault isolation.

Real Network

The methodology has been applied to a part of real MV network (220/22KV) shown in **Figure 4**, using DSL software. The network had 23 load points, 5 branches, 3 main feeders (A, B & C) feeder-A,B with 2 main section branch, feeder C with one section branch, 5 NC switches, and 3 NO switch (one of them is multiple). Now let us assume that the area enclosed by the dashed line has lost power because of the permanent fault on feeder A, then two study different scenario will be studied:

a. Case 1: without installed RCS switches.

b. Case2: with installed RCSC switches.

Afterthe fault isolation on the main feeder, A, the downstream loads are out-of-service. For each scenario, the first scenario considers manual switches and the second scenario considers remote controlled switch located at tie-open points because the power delivery should be restored quickly by closing a tie-line switch. However, this action may affect the distribution system's radial topology,thus needing flexible switching pair operations. To minimize the optimum number and allocation of switching pair operations, the program ends once the load is fully recovered and after meeting the constraints.

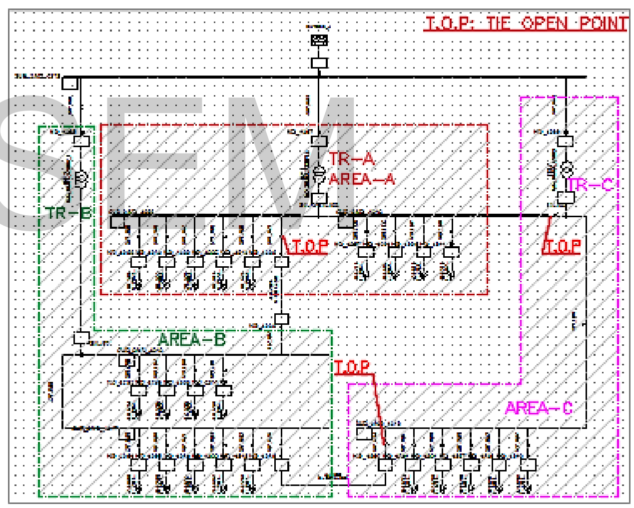

Figure 4: Real MV distribution system 66/22 KV.

TABLE-3
Restoration results of Real MV distribution network - first scenario with manual switches

Contingency: n-1
Fault location: (n-1)

Component:	FEEDER_A				
Station:	SUB_2				
Network:	SUB_02				
Repair Duration:		16.00 h (960 min)			
Failure frequency:		0.177 1/a			
Summary of failure effects					
		Power	Customers		
Interrupted:		13476.9 kW	5042		
Restored:	13476.9 kW (100.0 %)		5042 (100.0 %)		
Energy not supplied:		6122.2 kWh			
		1/failure	Yearly	Yearly (load state)	
Interruption costs:		40049.3 k$	7088.722 k$/a	*100.00 % = 7088.722 k$/a	

Time [min]	Step	Action	Device	Station		
0:00	Protection	Open	SW_1643	SUB_2		
					Interrupted:	13476.9 kW (100.0 %)

Time [min]	Step	Action	Device	Station		
30:00:00	Short Circuit Indicator	Open	SW_1625	SUB_2		
30:00		Open	SW_1628	SUB_2		
30:00		Open	SW_1634	SUB_2		
30:00		Close	SW_2150	TRFSTAT_504		
30:00		Open	SW_1608	SUB_2		
30:00		Close	SW_1316	TRFSTAT_504		
30:00		Close	SW_1623	SUB_2		
30:00		Close	1632	SUB_2		
				Interrupted:		
				Restored Power:		12201.9 kW (90.5 %)
				Restored Customers:		3666 (72.7 %)
				Totally Restored Power:		13476.9 kW
				Totally Restored Customers:		5042 (100.0 %)
					ENS:(0:00 - 1:00)	5897.6 kWh
					Total ENS:	6122.2 kWh
960:00 Repair:						
					ENS:(1:00 - 960:00)	0.0 kWh
						6122.2 kWh

However, in this paper, fault locating is based on the assumption that only the fault detectors between a faulted section and the substation circuit breaker have target set. Thus, the network is scanned until a section is found having a fault indicator set on one end, but not the other. With the faulted section specified, switches on either end of the faulted section will be opened. This is the fault isolation part.

ANALYSIS OF RESULTS

The program carries on network reconfiguration by opening and closing switches according to the switching optimization technique to restore power to consumers affected by the feederA outage. The optimum configurations of feederA, feederB, and feederC are obtained as follows:

1. For the fault case of feederA, the network was reconfigured bytaking a protection step by opening the substation circuit breaker andopening the two adjacent switches before and after the fault and then closing tie-switch (Tie_Sw_1625). Closing tie-switch (Tie_Sw_1634) allows transfer of load 13476.9 kW from feeder A to B and C.

2. For the fault case of feeder B, the network was reconfigured by closing NO tie-switch (Tie_Sw_1610) & (Tie_Sw_1634), allowing transfer of load 1350 kW from feeder B to feeder A and 1450 to C. Opening NC switches to splits lowers priority loads to avoid overloading on feeder A.

3. For the fault case of feeder C, the network was reconfigured by closing NO tie-switch (Tie_Sw_1625) & (Tie_Sw_1610), allowing transfer of load 1500 kW from feeder C to feeder A and 1500KW to B. Opening NC switch to splits lowerssplit load to avoid overloading on feeder A.

The results for the 3 pairs' best locations of RCS which give the minimum ENS for case (b) are shown in **Table 4**, aswell as the initial network ENS and reductionslevels (in k$/year and percentage) obtained with the new RCS switches location.

TABLE-4

Optimal RCS Placement for Real MV distribution network

Feeder:	FD_A
Backbones:	FD_A_12(1)
Number of new RCS per feeder:	1
Expected ENS:	60.046 MWh/a
Optimal RCS:	SW_1610
Feeder:	FD_B
Backbones:	FD_B_12(1)
Number of new RCS per feeder:	1
Expected ENS:	50.598 MWh/a
Optimal RCS:	SW_1625
Feeder:	FD_C
Backbones:	FD_C_1
Number of new RCS per feeder:	1
Expected ENS:	40.643 MWh/a
Optimal RCS:	SW_1634

Table 5 shows the obtained results for the network with three pairs of installed RCS switches.

The results show the following analysis for the simulated study cases. The highest value of initial ENS corresponds to the networks that do not have RCS switches installed (case a); the obtained value is 6122KWH/a. This value can be reduced to 224.5 k€/year when the networkhas threepairs of RCS switches (case b).These results seem to be consistent. The impact of installing RCS on the ENS depends on the location of these switches.This point has been obviously illustrated by the proposed algorithm, when applied to (b). The locations obtained for the switches with a minimum ENS are described in **Table 4**. The switches locations which lead to a minimum ENS and failure cost, considering all the situations studied for the network of Figure 4, correspond to case (b): the interruption cost found is 1398.5 k€ instead of 40049.3 k€ at case (a),reducingabout 90%. As it has been assumed that only one pairof switchescould be installed for every feeder, it is true that the presence of switches previously installed reduces the degrees of freedom for the optimal location of the RCS switches.

TABLE-5

Restoration results of Real MV distribution network - second scenario with 3 pair of RCS

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Contingency: n-1
Fault location: (n-1)
Component: TRF_8 2-Winding Transformer
Station: SUB_2
Network: SUB_02
Repair Duration: 16.00 h (960 min)
Failure frequency: 0.177 1/a

Summary of failure effects

	Power	Customers
Interrupted:	13476.9 kW	5042
Restored:	13476.9 kW (100.0 %)	5042 (100.0 %)

Energy not supplied: 224.6 KWh

	1/failure	Yearly	Yearly (load state)
Interruption costs:	1398.5 k€	247.542 k€/a	*100.00 % = 247.542 k€/a

Time [min]	Step	Action	Device	Station	
0:00	Protection	Open	SW_1643	SUB_2	
				Interrupted:	6665.0 kW

Time [min]	Step	Action	Device	Station
1:00:00	Remote Controlled	Open	SW_1610	SUB_2
1:00:00		Open	SW_1625	SUB_2
1:00:00		Open	SW_1634	SUB_2
1:00:00		Close	SW_1623	SUB_2
1:00:00		Close	SW_1632	SUB_2
1:00:00		Close	SW_2150	SUB_2

Interrupted:	
Restored Power:	13476.9 kW (100.0 %)
Restored Customers:	5042 (100.0 %)
Totally Restored Power:	13476.9 kW (100.0 %)
Totally Restored Customers:	5042 (100.0 %)

TABLE-6
Results of reliability summary for Real Network.

	No of RCS	SW "ID"	Action	Reason	ENS (MWh/a)	Interruption cost (k$)
Case1	-	-	-	-	6122.2	40049.3
Case2	3	- SW_1610 - SW_1625 - SW_1	- Open - close - close	-Clear fault -Power restoration -Power restoration	224.6	1398.5

		634				

Table 6 shows the results comparison between the two previous cases.

CONCLUSIONS

Due to the increasing size and complexity of distribution networks, using practical software for the simulation and analysis of such networks became a necessity. Power restoration is an important process since faults cannot be avoided till time repair. In this paper, the DSL software is used as a tool for this calculation. The results show that installing optimal number and allocation of RCS are used to isolate a fault and restore the power for maximum number of consumers.Thebenchmark and part of real MVradial distribution networkhave been simulated, with accurate load flow analysis and optimal reconfiguration of the network.

Proper power restoration to all consumers was achieved and also the objective function was achieved,meeting all the network constraints such as lines capacity and operating current and voltage limitations, so different approaches have been considered in this work for decreasing ENS and the annual cost in this power restoration, such as addition of RCS switches in the network. These remedial actions for the fast restoration case can also enhance the reliability all over the network and the performance ofit during normal operation.

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