J. Electromagnetic Analysis & Applications, **2009, 2: 85-91**
doi:10.4236/jemaa.2009.12013 Published Online June 2009 (www.SciRP.org/journal/jemaa)

Distance Measure Based Rules for Voltage Regulation with Loss Reduction

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Received March 19th, 2009; revised May 25th, 2009; accepted May 28th, 2009.

ABSTRACT

This paper presents a rule-based technique to control the voltage in a power transmission network. Transformers with a tap changer installed in the system are selected by the proposed technique as control devices. For each bus under voltage violation, the most effective control device is selected by using the minimum electric distance criteria. In order to demonstrate the efficiency of the method, several simulations were performed using an IEEE 30-bus network as a model system. The distance measure technique is compared with classic voltage regulation approach and a genetic algorithm based. The results obtained show the robustness of the proposed method.

Keywords: *Knowledge Based Systems, Losses, Voltage Control*

1. Introduction

Current approaches to the operation of a modern distribution network demand high operational performance of the system and consequently require highly effective control strategies. Although voltage deviation control is one of the problems that has been extensively investigated, it still remains as an important topic to deal with. Voltage control algorithms may be classified into two categories: rule-based and network model-based. Rule-based algorithms use rules that control switched capacitors and transformer tap changers based on real-time measurements and past experience. Network model-based systems use network topology, impedance, real-time measurements and statistical information to establish the current state of the system. It then applies optimization techniques to get the best possible solution. Within the network models-based systems there are many different approaches. A simulated annealing technique for global optimal solution is presented in [1]. The authors propose a knowledge-based expert system which detects buses with maximum voltage deviations and operates the nearest available transformer control unit to correct the problem. Then, a simulated annealing algorithm is utilized to solve the problem of capacitors manipulation. The paper shows a very good result in terms of power loss reductions but does not guarantee an economical use of transformers operations. Restriction in the number of switching operation is the focus in [2]. Here, dynamic programming and fuzzy logic algorithms are combined to control voltages and reduce power losses. The problem is decomposed into two sub-problems: first, the control of the load tap changers (LTC) and capacitor banks at substation level and second, the control of the capacitor banks installed at the feeder level. Dynamic programming is used in sub-problem 1 and fuzzy logic is adopted for the second sub-problem. Simulation results show the excellent performance of the proposed approach. The use of genetic algorithms is another approach to the control of voltage and reactive power in the system. The approach in [3] combines the benefits of a linearized system model and genetic algorithms (GA). Whenever a voltage correction is demanded, an initial calculation of the sensitivity matrix is done in order to identify an initial population for the GA. Then the GA finds a proper set of control actions to execute. The method offers good solutions to the voltage/reactive power problem and also reduces the number of control actions. Authors in [4] use a method based on an artificial neural network to find the suitable capacitor switching regime for every load state. The main objective is to reduce power losses and the only constraint considered is bus voltage. The advantage of this method is the short calculation time. However, in real applications, it might be difficult to use because the system requires training sessions every time any small change is made to the network topology.

The approach presented in this paper is rule-based and is a new decision-making tool for centralized control of voltage. When the system lacks automatic function control the task has to be performed manually by the supervisor in the dispatch center. Due to the complexity of a modern power system and the severe consequences to the economy of power failures, reliable algorithms have to be part of the daily support tools in the dispatch center. This research was motivated by the necessity to design a simple and effective support algorithm for the voltage control process. The algorithm is based on the identification of a bus having the worst voltage violations and the nearest bus where a voltage control device is installed. A control device setting is changed in order to improve the voltage situation of the bus in violation. A 30 bus network was used as a case study. Some classic control elements such as transformers with tap changers, shunt capacitor banks, synchronous condensers, and generators were modeled. Although the control strategy reported here is focused on tap changer, is possible to use all installed devices as controllable elements. The important features of the case study system, the proposed method, and the search algorithm are explained in Sections 2−4. Simulation results of the 30-bus system under different load conditions are discussed in Sections 5 and 6.

2. Case Study System

The modeled system is an IEEE 30-bus scheme. The system bus data is given in Table 1, and with Figure 1 showing the single line diagram. Shunt capacitor banks are located at bus 10 and 24. The capacitor bank found at node 10 contains up to 10 units with a reactive power capacity of 1.9 Mvar for each unit. In the case of bus 24, banks have been installed containing up to 3 units of 0.8 Mvar each

Table 1. Bus data

Name	Type	V(p.u)	Pg(p.u)	Qg(p.u)	Pd(p.u)	Qd(p.u)
1	S	1.030			0.0	0.0
2	PV	1.036	0.4		0.217	0.127
3	PQ		0.0	0.0	0.024	0.012
4	PQ		0.0	0.0	0.076	0.016
5	PV	0.97	0.0		0.942	0.19
6	PQ		0.0	0.0	0.0	0.0
7	PQ		0.0	0.0	0.228	0.109
8	PV	0.98	0.0		0.3	0.0
9	PQ		0.0	0.0	0.0	0.0
10	PQ		0.0	0.0	0.058	0.02
11	PV	0.99	0.0		0.0	0.0
12	PQ		0.0	0.0	0.112	0.075
13	PV	0.985	0.0		0.0	0.0
14	PQ		0.0	0.0	0.062	0.016
15	PQ		0.0	0.0	0.082	0.025
16	PQ		0.0	0.0	0.035	0.018
17	PQ		0.0	0.0	0.09	0.058
18	PQ		0.0	0.0	0.032	0.009
19	PQ		0.0	0.0	0.095	0.034
20	PQ		0.0	0.0	0.022	0.007
21	PQ		0.0	0.0	0.175	0.112
22	PQ		0.0	0.0	0.0	0.0
23	PQ		0.0	0.0	0.032	0.016
24	PQ		0.0	0.0	0.087	0.067
25	PQ		0.0	0.0	0.0	0.0
26	PQ		0.0	0.0	0.035	0.023
27	PQ		0.0	0.0	0.0	0.0
28	PQ		0.0	0.0	0.0	0.0
29	PQ		0.0	0.0	0.024	0.009
30	PQ		0.0	0.0	0.106	0.019

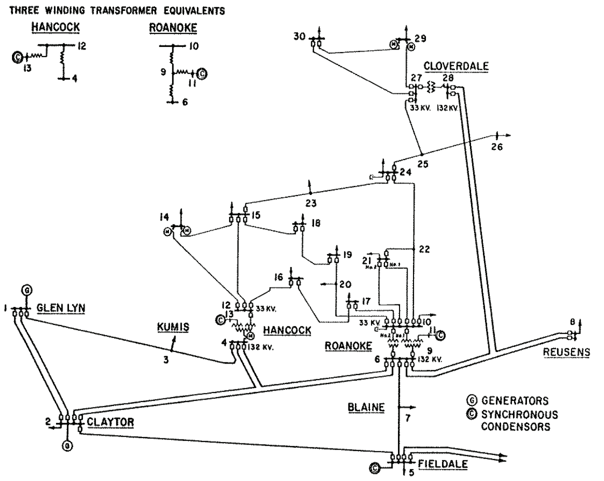


Figure 1. 30-bus IEEE scheme

one. The tap changer settings ranges are modeled at settings from 0.9 to 1.1 with a step of 0.01 per unit. Four synchronous condensers are also considered at buses 5, 8, 11 and 13.

3. Proposed Method

Usually, the system is exposed to overload and under-load conditions in 24 hour intervals. When the system is in the overload condition, transferred power trough lines and transformers might causes excessive voltage drops and consequently appear bus voltages below the minimum limit. In the case of an under-load condition, shunt capacitance of the lines inject an excessive reactive power into the network and the voltage in some buses might be above the maximum limit. A safe voltage operation range is considered to be from 0.95 to 1.05 per unit. A rule-based approach is proposed to bring the system to a normal point of operation, with rules being presented in Table 2. The ranking list order is based on the electrical distance criteria between every voltage control device and the target bus. Once the nearest voltage control device is selected, the device settings have to be modified using a minimum number of steps in order to avoid unnecessary control actions.

Table 2. Voltage control procedure

Step1: Perform the power flow calculation. If there is any violation of voltage then move to step 2. If not then move to step 4.
Step2: Identification of the bus under the worst voltage condition as target bus. Creation of a ranking list of voltage control devices.
Step3: Identification of the device located at the first position of the ranking as optimal control device. If is not available, due to settings reaching upper/lower limits, then the device in the next ranking position is selected as the optimal control device. If is available, then perform setting modifications at the optimal control device. Return to step 1. If there is not any more control action possible and the target bus remains as same bus, then move to step 4.
Step4: The calculation is stopped.

4. Distance Measure Algorithm

The shortest route from the bus under worst voltage condition to a corresponding control device location is calculated using Dijkstra's algorithm [5]. The basic operation of this algorithm uses edge relaxation. In this case, the edges are the electrical distance L_{ij} of the transmission line between buses i and j. The electrical distance is defined in (1).

$$L_{ij} = \sqrt{R_{ij}^2 + X_{ij}^2} \quad (1)$$

where

R: is the resistance of brach i-j

X: is the reactance of brach i-j

Once the minimum paths are found, a ranking of distance measures is established in order to develop a decision strategy to solve the problem of voltage violation.

5. Simulation Results

For the controllable devices to have a long operating life it is vital to avoid unnecessary control actions. Therefore, only strictly necessary actions are allowed. A control effort index, CEI, is defined to count the number of control actions used in every simulation. The CEI definition is presented below.

$$CEI = \sum_{i=1}^{n} \left| tap_i^s - tap_i^{ref} \right| \quad (2)$$

where

i: is the i-th controllable device

s: actual tap position of the i-th controllable device

ref : is the reference tap position of the i-th controllable device

In the initial state of the system, the voltage violations are under the minimum voltage limit. It was for this reason that the shunt capacitors were not adjusted in these simulations. Also, it is important to note that the minimum tap modification is 0.01 in per unit so that if the CEI value is 0.36, it means that 36 operations of the tap were made.

The simulation results are shown in three parts. The first part is a comparison between a local control strategy, an evolutionary search based on a genetic algorithm and the distance based method. The second part illustrates the performance of the proposed method under a load variation during a period of 24 hours. In the last section, there is also a power losses analysis.

5.1 A Comparison of Voltage Local Control, Genetic Algorithm Based Correction, and the Proposed Voltage Control Algorithm

Voltage local control is a classic method based on the local monitoring and operation of each control device. It means that at every node where a control device is installed, a local and independent control strategy is followed, and control actions are executed exclusively where voltage problems appear. Figure 2 illustrates an initial voltage profile of the network under a hypothetical load scenario which is assumed to be the maximum load scenario. The voltage profile shows several nodes violating the minimum voltage limit. Buses which are under violation and where a control device is installed are marked with a circle. In this initial condition only transformer operations are available because all capacitor banks are already connected.

Table 3 lists the positions of transformer taps in the initial state, during two partial solutions and for the final solution. The final solution is reached when the four buses highlighted in Figure 2 are out of the violation zone. The final solution, shown in Figure 3, does not solve the problem of voltage at nodes other than those where the control devices are installed.

The second reference point for this comparison is a genetic algorithm (GA). GAs are considered more flexible and robust than most of deterministic search methods because it requires only information concerning the quality of the solution produced by each parameter set. This is unlike many traditional methods that require derivative information or worse yet, completed knowledge of the problem structure and parameters [6]. For this GA, decision variables are expressed as integers. Each gene represents the tap position of a transformer. Integer variables are used in order to avoid unnecessary coding and recoding. By using this non-binary coding, which is a closer representation of real system parameters, it is expected that there should be an increment in the velocity of convergence [7]. The representation of one individual is shown in Figure 4. The initial population is generated randomly.

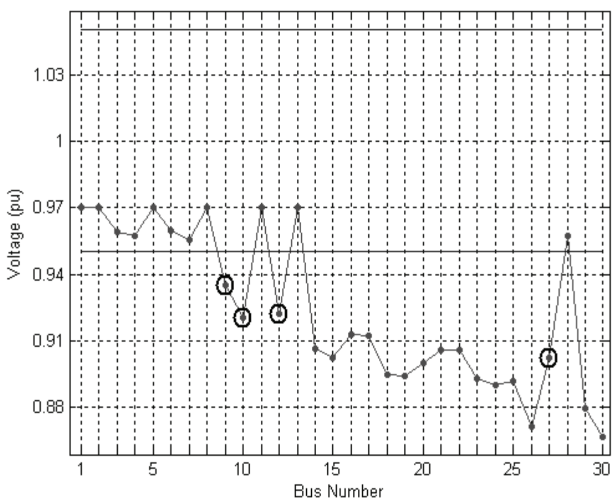


Figure 2. Voltage profile of the network obtained for initial conditions

Table 3. Operation of the controllable devices using the control method of local voltage

	Bus Number		Tap(p.u)			
Name	Sending	Receiving	Initial	1	2	Final
T1	6	9	0.97	**1.00**	1.00	**1.04**
T2	6	10	0.96	**0.99**	**1.01**	**1.02**
T3	11	9	1.00	1.00	1.00	1.00
T4	9	10	1.00	1.00	**0.91**	0.91
T5	4	12	0.93	0.93	0.93	0.93
T6	13	12	1.00	**1.03**	**1.05**	**1.06**
T7	28	27	0.96	**1.00**	**1.02**	**1.04**
CEI			0.00	0.13	0.15	0.08
Total CEI			0.36			

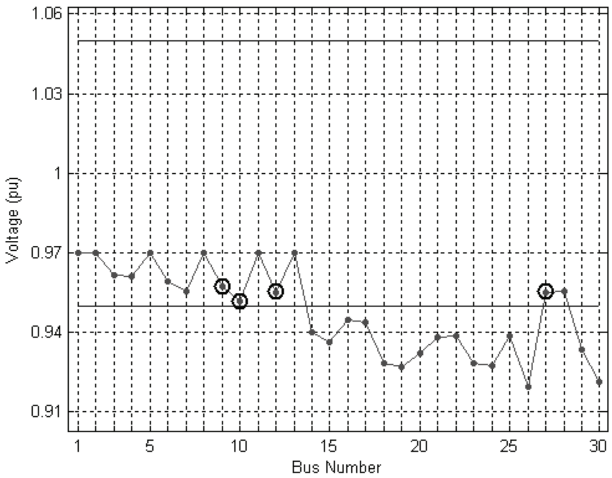


Figure 3. Voltage profile of the network obtained after execution of voltage local control

+1	0	-5	+8	-10	+3	0
T1	T2	T3	T4	T5	T6	T7

Figure 4. Integer representation of one individual

Then, chromosomes are evaluated through a fitness function (see Equations 3 and 4) where the objective function is the minimum number of adjustments to the tap changers. The voltage deviation at each bus, the reactive limit violation at each generator and maximum line current limit are considered as constraints. The evaluation is based on Newton-Raphson power flow calculations, provided by the MatPower package [8]. The genetic operators are tournament selection, one-point crossover, and uniform mutation. The stopping criterion is the number of generation being 60 with the probability of mutation being 15%.

$$\min\left(\sum\left|tap_i^s - tap_i^{ref}\right| + R\right) \quad (3)$$

and

$$R = a * vd + b * ql + c * cl \quad (4)$$

where

s: actual tap position
i: ith-tap transformer
ref : reference of tap position
vd: violation of voltage deviation
ql: violation of generated reactive power
cl: violation of current in lines
a: weight for violation of limits of voltages
b: weight for violation of limits of generated Var
c: weight for violation of limits of current flowing through lines

In order to get a clear solution with the GA, a total of 45 independent simulations were executed with a common initial condition, (the conditions being as shown in Figure 2). Figure 5 shows the mean value of voltage deviation factor at each generation. The mean value of number of control actions are shown in Figure 6, where most of the simulations reach a common solution with fewer than 43 operations. The mean value of fitness for each generation are illustrated in Figure 7. In these three Figures each curve represent one of the 45 simulations. The superposition of the curves demonstrates the similarity of the solutions for each simulation. The best solution at each simulation are shown in Figure 8. With 41 control operations being the minimum value that can be reached by the GA. The best solution for each simulation has no constraint violations. For example, Figure 9 shows the best solution for the voltage profile simulation number 45.

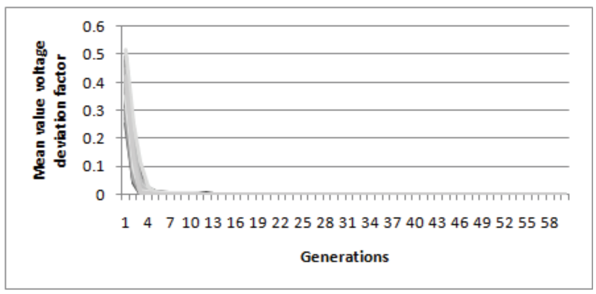


Figure 5. Mean value of voltage deviation factor for the 45 simulations

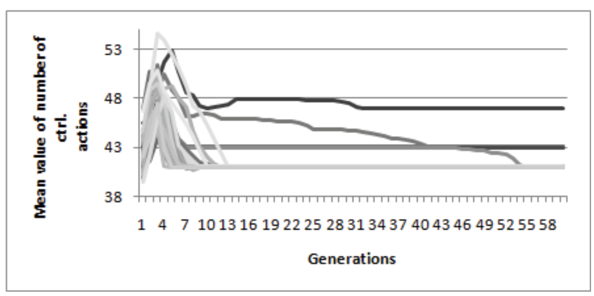


Figure 6. Mean value of the number of operations for the 45 simulations

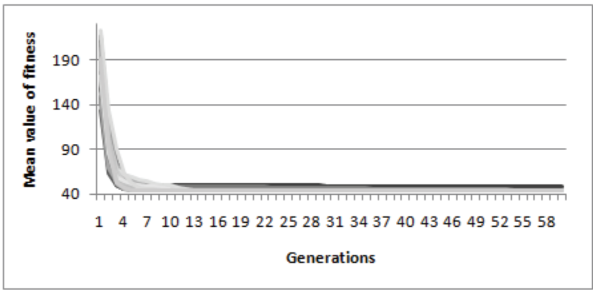


Figure 7. Mean value of fitness for the 45 simulations

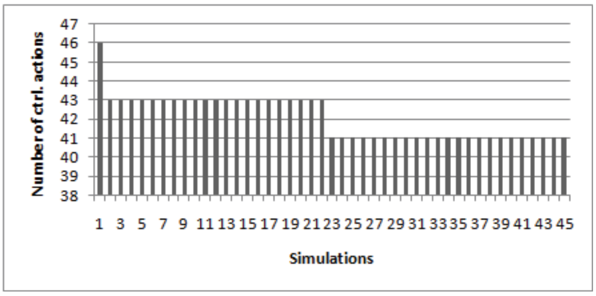


Figure 8. Number of control action for the best solution at each simulation

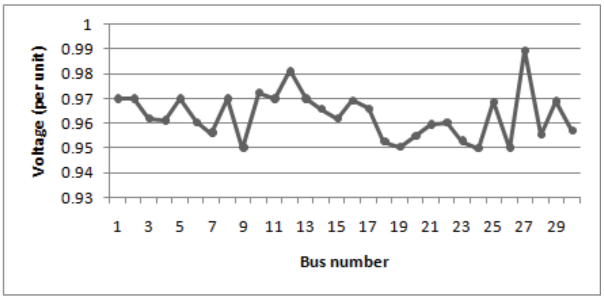


Figure 9. Voltage profile for the best solution at simulation number 45

Table 4. Operation of the controllable devices using the distance measure method

	Bus Number		Tap(p.u)			
Name	Sending	Receiving	Initial	1	2	Final
T1	6	9	0.97	0.97	0.97	**1.03**
T2	6	10	0.96	**0.99**	**1.06**	**1.10**
T3	11	9	1.00	1.00	1.00	1.00
T4	9	10	1.00	1.00	1.00	1.00
T5	4	12	0.93	0.93	0.93	0.93
T6	13	12	1.00	1.00	**1.02**	**1.09**
T7	28	27	0.96	**1.04**	**1.05**	**1.09**
CEI			0.00	0.11	0.10	0.21
Total CEI			0.42			

In the case of the proposed rule-based method, the initial state is the same as that showed in Figure 2. The worst voltage is located at node 30 and transformer T7 is the best control device to solve the problem. The tap position in transformer 7 was moved from 0.96 to 1.00 and the voltage problem in node 30 was solved. Then bus 19 appeared as the worst bus and the most effective control device was transformer 2. The process was repeated several times until a final solution was reached. Table 4 shows the initial conditions of tap positions, two partial solutions and the final solution. Values in boldface font

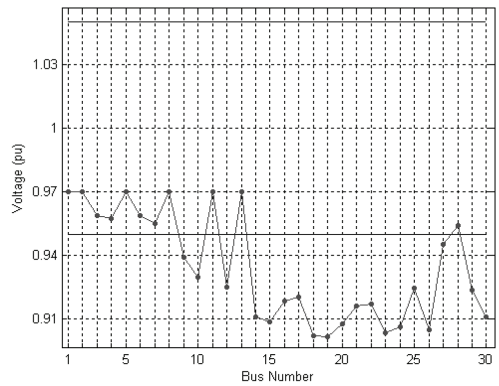


Figure 10. Voltage profile of the network obtained in sub-solution 1

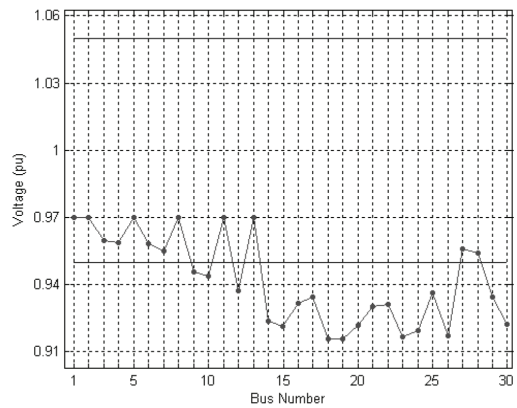


Figure 11. Voltage profile of the network obtained in sub-solution 2

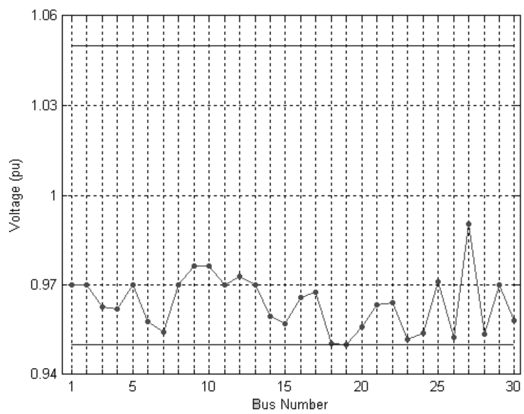


Figure 12. Voltage profile of the network obtained in the final solution

represent a new modification of the tap position. In Figure 10, 11 and 12 the voltage profile for the two partial solutions and the final result are presented respectively. Final voltage profile shows the capacity of the rule-based method to find a suitable solution, and the total CEI=0.42, means that the number of control actions is 42, which is very close to the optimal solution of the GA-based method.

5.2 Performance of the New Method Applied for a Load Variation over a 24 Hour Interval

It is well known that power demand in a real system is changing continually during the day, and consequently state variables are varying as well. Thus, it is necessary to study the effectiveness of the proposed method for this typical behavior. Load variation was modeled as coincident in time. Appendix A shows the percentage of the rate load at every bus and the voltage at 6 buses after application of the distance measure method. Other than the buses shown in Appendix A, the rest are kept within the non-violating voltage zone. The variations in the transformer taps are illustrated in Appendix B. In the case of capacitor bank adjustment, none were executed because all the banks were connected in the initial state and the voltage violations that appeared were of the under-voltage type.

6. Analysis of Power Loss Reduction

In addition to voltage correction, power losses were also monitored and analyzed. This new control method yields a very flat voltage scenario which is very important in order to reduce power loss. Appendix C illustrates how the power losses are reduced gradually in each partial solution obtained by the proposed method. The final solution gives a 0.67 % power loss reduction.

7. Conclusions

In this paper a Rule-based method was presented for regulating voltage deviations and to reduce power losses of a transmission system. The control method is based on simple rules. Which allow to operate only the most effective devices to solve voltage violations. Thus, control actions were executed under the principle of imposing the fewest number of operations of control devices. Several simulations were done to compare a local voltage control strategy and GA-based method with the new method. The results proved that:

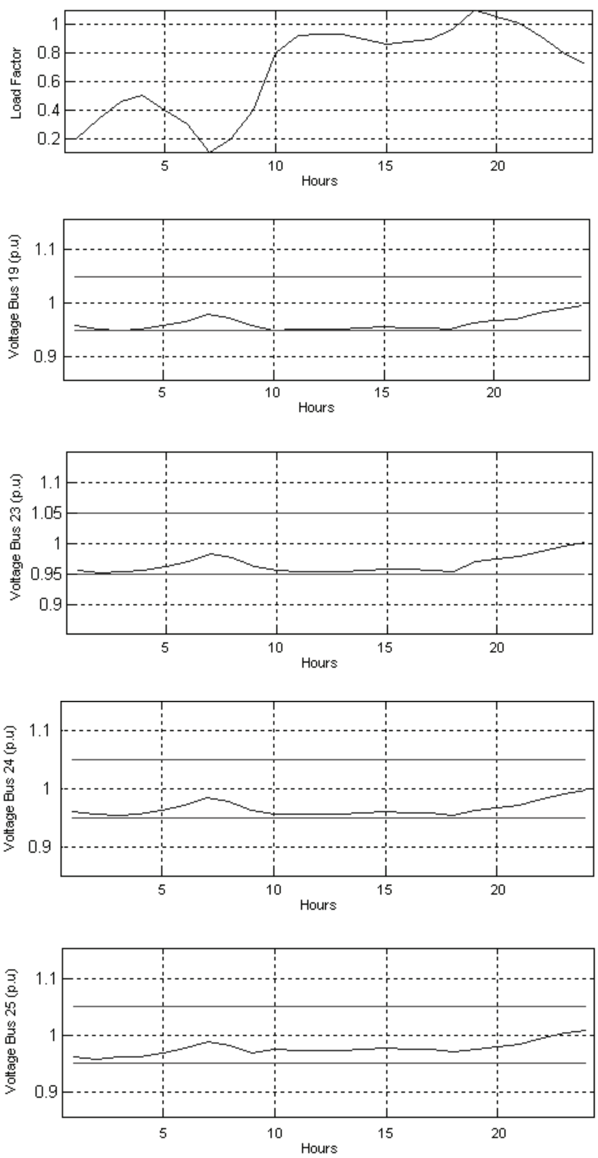
1) The new method achieves the goal where the local voltage control strategy fails. The most important issue, which is voltage correction, is not successfully accomplished with the approach based on local control.

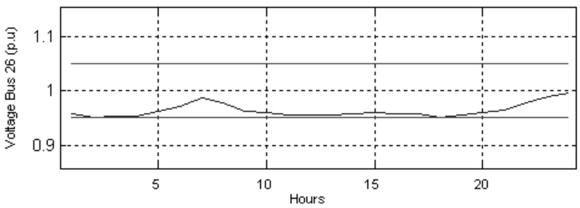
2) The rule-based method was compared with several simulations of a GA-based method and the results are very similar. The number of control actions from GA-approach is 41 while for the rule-based method is 42. There are no constraint violations in the solutions provided by both methods.

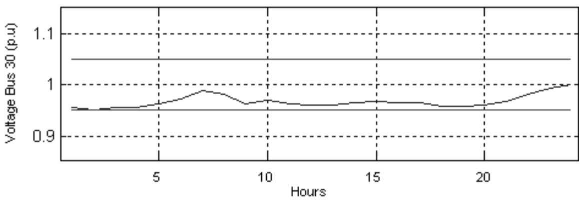
3) The rule-based method significantly reduces power losses of the system under maximum load condition and under a load variation period of 24 hours. Voltages at all buses were maintained out of the voltage violation zone.

4) Although the proposed method is based on very simple rules, where significant approximations are used to determine a ranking list of effective controllable devices, this approach can be used as a useful, simple and fast tool for dispatcher engineers in a situation requiring correction of voltages.

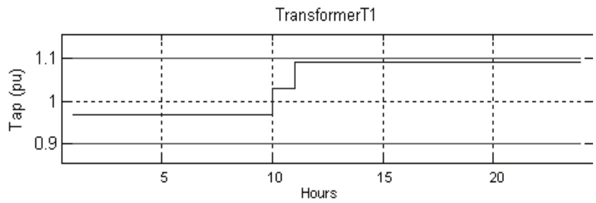
Appendix A

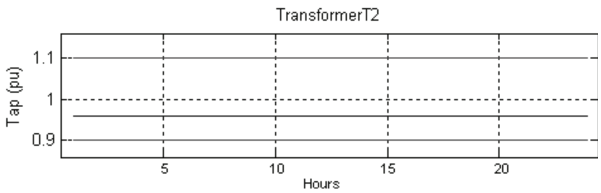


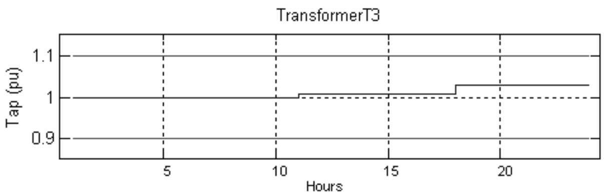


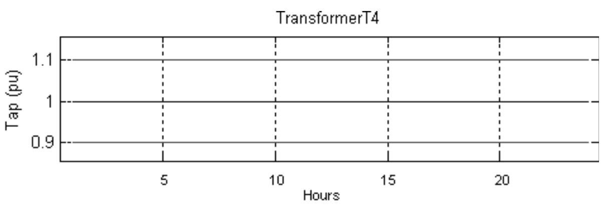


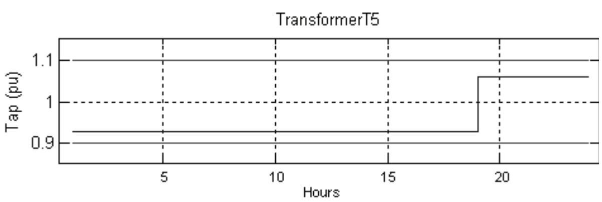
Appendix B

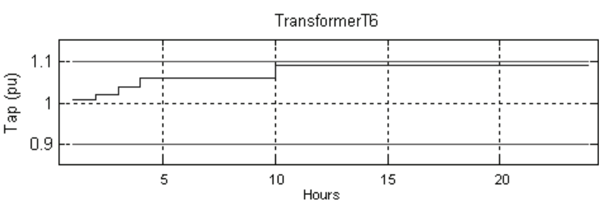


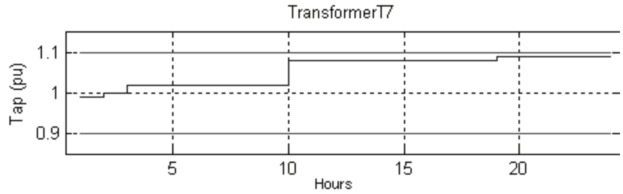




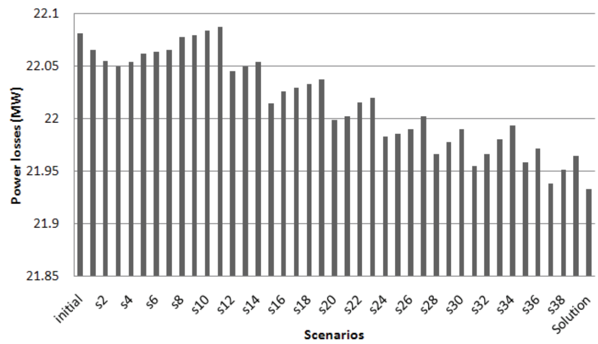








Appendix C



REFERENCES

[1] T. Ananthapadmanabha, "Knowledge-based expert system for optimal reactive power control in distribution system," International Journal of Electrical Power and Energy Systems, Vol. 18, pp. 27–31, January 1996.

[2] Y. T. Liu, Z. G. Peng, and X. Z. Qiu, "Optimal volt/var control in distribution systems," International Journal of Electrical Power and Energy Systems, Vol. 24, pp. 271–276, May 2002.

[3] Y. Malachi and S. Singer, "A genetic algorithm for the corrective control of voltage and reactive power," IEEE Transactions on Power Systems, Vol. 21, pp. 295–300, February 2006.

[4] B. Das and P. K. Verma, "Artificial neural network-based optimal capacitor switching in a distribution system," Electric Power System Research, Vol. 60, pp. 55–62, June 2001.

[5] H. I. Hagenaars, J. Imura, and H. Nijneijer, "Approximate continuous-time optimal control in obstacle avoidance by time/space descrifization of non-convex state constraints," Proceedings of 2004 IEEE Conference on Control Applications, pp. 878–883, 2004.

[6] K. Y. Lee and M. A. El-Sharkawi, "Modern heuristic optimization techniques: Theory and applications to power systems," New Jersey: Wiley-IEEE Press, pp. 173, 2008.

[7] Y. Rosales and T. Hiyama, "A review of genetic algorithms implemented for voltage/var optimization problems in electric network systems," submitted for publishing.

[8] MATPOWER, http://www.pserc.cornell.edu/matpower/.

