

Positioning of multicapacitors in a radial distribution network using new analytical methods

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Abstract— This paper consisted of sizing and positioning multiple capacitors at multi-node in the Maradi HV distribution network in Niger by a new modern analytical method based on the calculation of a stability identification index (BVSI). From this study, it is observed that the positioning of the 2100 kVAr, 1050kVAr, and 2100 kVAr power capacitors at node 31, node 84 and node 105 respectively in the 123-bus network of Maradi contributed to reducing the losses of this network by 20.71% with a minimum voltage of 0.9172 pu. However, despite this improvement, 31.70% of the nodes still remained within the critical ranges, hence the need for other equipment to improve the performance of distribution networks. The traditional means of improving the technical performance of distribution networks by means of capacitors is nowadays insufficient to maintain the indicative parameters of the technical performance of distribution networks in emerging countries within the normative limits.

Keywords—Bus Voltage Stability Index (BVSI); Placement optimal; High-voltage (HV)

I. INTRODUCTION

The reduction of losses and the maintenance of voltages within the normative ranges of the EN 15160 reference constitute the daily operations of the distributors in order to comply with the binding requirements of their customers and the regulator by looking at the data collected on the performance of the electrical networks. The progressive degradation of African electricity systems is generally due for the most part to the excessive flow of reactive currents and harmonics on the systems. In several West African countries, the operators add compensation capacitors either in the source substations or in the distribution substations in order to provide reactive power to compensate the networks globally. This solution has shown its limits in terms of efficiency. Indeed, some capacitors placed in EHV/HV source substations or in HV/HV distribution substations fail to effectively and sustainably improve the technical performance of electrical networks. In addition to this problem, the inappropriate sizing

of these capacitors leads to consequences such as overvoltages that can cause the breakdown of certain network equipment. Several scientists have proposed methods to solve the problem of optimal sizing and the determination of the number of capacitors at the saturation limit. Thus, in 2010, Abdellatif Hamouda et al [1] used the Markov chain-based method for positioning capacitors at sensitive nodes. It appears that this method is more efficient than the methods previously developed in the literature. In 2012, Chien-Feng Yang et al [2] worked on the optimal placement of compensation devices (SVC) in distribution systems using hybrid differential evolution that combines source substation transformer taps and stability indices. They found this technique to be very effective in improving the performance of a distribution network. In 2014, EL Fergany et al [3] worked on the cuckoo search optimization algorithm for positioning static shunt capacitors in distribution networks. They concluded that the results shown by this method surpassed the results of existing heuristics. In 2016, A.Y. Abdelaziz et al [4] proposed the flower pollination algorithm (FPA) to solve the problem of optimal capacitor placement in distribution networks. According to the authors, the algorithms used in the literature cannot achieve the optimal cost, and that the FPA effectively decreases the total active power losses, total cost and enhances the voltage profiles for different distribution systems. In this paper, a new analytical method is presented to size and position capacitors at multiple nodes of a distribution network.

II. TRADITIONAL ANALYTICAL METHODS OF PLACING CAPACITORS IN NETWORKS

In the past, several authors have proposed analytical methods for capacitor placement in distribution systems. The relevance and efficiency of these methods are still debatable according to the different feedbacks from their applicability. Most of these methods use power flow analysis. These different methods are tested respectively on the IEEE 69-bus network and on the 123-bus network in Maradi.

A. Node Voltage Stability Indices

Voltage instability in a network is the starting point for network collapse. Consequently, network managers are working to anticipate the catastrophic collapse phenomenon by evaluating the areas of the network likely to be at the origin of the voltage instability by means of indices [5]. In this section, four commonly used bus voltage indices are presented.

- Voltage Stability Index (VSI): In [6], the stability index is calculated to determine the critical nodes. Lower VSI values indicate unstable nodes. The expression of the VSI depends on the quality of the active and reactive power flow and the voltage.

$$VSI_{i+1} = |V_i|^4 - 4(P_{i+1}X_{i+1} - Q_{i+1}R_{i+1})^2 - 4(P_{i+1}R_{i+1} + Q_{i+1}X_{i+1})|V_i|^2 \quad (1)$$

- Equivalent Node Voltage Collapse Index (ENVCI): In [7], when the ENVCI of at least one node is close to zero, the system approaches the voltage collapse point. Equation (2) shows the expression for ENVCI.

$$ENVCI = 2E_k V_n \cos \theta_{kn} - E_k^2 \quad (2)$$

- Voltage Stability Factor (VSF): In [8], the closer the VSF value is to zero, the more vulnerable the system is. At each node the VSF is calculated using (3).

$$VSF_{m+1} = (2V_{m+1} - V_m) \quad (3)$$

- Stability Index (L): In [9], nodes with L values close to unity are identified as critical nodes.

$$L = 4 \frac{V_i^2(P_{i+1}R_i + Q_{i+1}X_i) + (P_{i+1}X_i - Q_{i+1}R_i)^2}{V_i^4} \quad (4)$$

B. Line Voltage Stability Indices

In order to further investigate vulnerabilities in their network, power system operators sometimes resort to checking the stability of their power lines and feeders. To this end, several line voltage stability indices have been developed to identify lines with weaknesses, including the Lmn, LQP, FVSI, VCPI, NLSI and LVSI indices, which we will use in this paper to explore the voltage criticality of network lines.

- Line Stability Index (Lmn): Moghavvemi in [10], the Lmn of each line should be kept to less than unity to ensure a stable system.

$$L_{mn} = \frac{4Q_r X}{[V_s \sin(\theta - \delta)]^2} \quad (5)$$

- Line Stability Factor (LQP): In [11], for stable operation, the LQP value of each line must be less than 1.

$$LQP = 4 \left(\frac{X}{V_i^2} \right) \left(\frac{X}{V_i^2} P_i^2 + Q_i \right) \quad (6)$$

- Voltage Collapse Proximity Indicator (VCPI): In [12], the critical lines will be determined by the power and loss indicators approaching threshold 1.

$$VCPI(\text{power}) = \frac{P_r}{P_{r(\max)}} \quad (7)$$

$$VCPI(\text{loss}) = \frac{P_l}{P_{l(\max)}} \quad (8)$$

Where P_r is the active power at the receiving node and P_l is the active power lost in the line

- Novel Line Stability Index (NLSI): In [13] the NLSI stability index is determined from the quadratic voltage of a line in a two-nodes system. The threshold of "1" indicates that the line has reached its instability limit

$$NLSI_{ij} = \frac{R_{ij}P_j + X_{ij}Q_j}{0.25V_i^2} \quad (9)$$

- Fast Voltage Stability Index (FVSI): The fast voltage stability index proposed by I. Musirin in [14], is used to predict the voltage drop point in an electric power transmission line. When the FVSI is close to 1 the system is at the limit of stability, and the line for which this index is calculated is said to be the most sensitive of the system.

$$FVSI_{ij} = \frac{4Z^2 Q_j}{XV_i^2} \quad (10)$$

- Line Voltage Stability Index (LVSI): In [15], for stable operation, the LVSI value must be below the threshold 1

$$LVSI = \frac{4P_r R}{V_s \cos(\theta - \delta)^2} \quad (11)$$

III. NEW METHOD OF INDEX CALCULATION BY BUS VOLTAGE STABILITY INDEX (BVSI)

This new method is based on the ratio of incoming voltage to outgoing voltage on HV lines. Considering a two-nodes system in which an elementary generator is injected as shown in Fig 1.

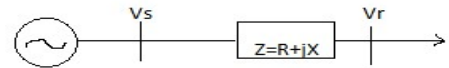


Fig.1. 2- Bus system line

The voltages V_s and V_r are given by the power flow solution. The voltage at any node "i" is then equal to:

$$\bar{V}(i) = \bar{V}(i-1) - \bar{Z}(i)\bar{I}(i) \quad (12)$$

$$\begin{cases} \bar{Z}(i) = R(i) + jX(i) \\ \bar{I}(i) = \left(\frac{\bar{S}(i)}{\bar{V}(i-1)} \right)^* \end{cases} \quad (13)$$

With respectively $\bar{Z}(i)$, $\bar{I}(i)$, $\bar{S}(i)$ the impedance of the branch, the current in this branch and the apparent power at the beginning of this branch. The BVSI is given by the expression (14). The critical and neuralgic sets of bars that could be

identified as compensators have low BVSI values in the interval [0, 1].

$$BVSI = \frac{3V_r - V_s}{2V_r} \quad (14)$$

IV. CALCULATION OF THE POWER FLOW AND THE OPTIMAL SIZE OF THE CAPACITORS

In this article, we have used the BIBC (Bus injection - Branch current) power flow method associated with the grid voltage stability index calculations. The size of the capacitor is calculated using the variational technique. First, the initial load flow is done to find the weak nodes for each index and the losses. Then the optimal size of the capacitor is calculated. The calculation algorithms are as follows:

A. Algorithm of Power Flow

- Step 1: Read network data in p.u
- Step 2: Read the tolerance ε
- Step 3: Read base power and voltage
- Step 4: Initialization of nodal voltages at 1 p.u
- Step 5: Initialization of iterations, $K=1$
- Step 6: Formation of BIBC and BCBV matrix
- Step 7: Calculation of current injections $[I]$ at the different nodes as follows:

$$\bar{I}_i = \left(\frac{S_i}{V_i} \right)^* \quad (15)$$

- Step 8: Calculation of branch currents by:

$$[J] = [BIBC][I] \quad (16)$$

- Step 9: Calculation of voltage drop in each branch by:

$$[\Delta V^{k+1}] = [BCBV][J] \quad (17)$$

- Step 10: Calculation of new nodal voltages, $[V^{k+1}]$ by:

$$[V^{k+1}] = [V^0] - [\Delta V^{k+1}] \quad (18)$$

- Step 11: if $\max ([V^{k+1}] - [V^k]) < \varepsilon$, go to step 12, otherwise return to step 7
 - Step 12: Calculate the VSI, ENVCI, VSF, L, Lmn, LQP, VCPI, NLSI, FVSI, LVSI, BVSI for each node
 - Step 13: Calculate total active loss by:
- $$P_{T,loss} = \sum_{i=1}^b R_i * |I_i|^2 \quad (19)$$
- Step 14: Calculate total reactive loss by:
- $$Q_{T,loss} = \sum_{i=1}^b X_i * |I_i|^2 \quad (20)$$
- Step 15: Show power flow solutions.

B. Optimal Capacitor Size Calculation by the variational Technique

- Step 1: Read line data and bus data and find candidate bus for capacitor placement for each index.
- Step 2: Place the capacitor on the candidate bus with a size varying in steps of 50 KVar.
- Step 3: Find the losses after placing the capacitor.
- Step 4: Select the capacitor size that gives minimum losses.

- Step 5: Stop.

V. RESULTS AND DISCUSSIONS

The algorithm developed in this study was successively tested on an IEEE 69-bus distribution systems and on the Maradi rural electrification 123-bus in Niger.

A. IEEE 69-Bus Distribution Network

The network diagram shown in Fig. 2 is that of a 69-bus IEEE network [16], which was used in this paper to test the developed algorithm and to calculate the different indices. Base voltage and power of this network, 12.6 KV and 1 MVA. Fig 3. shows the voltage profile of this network. It is observed that 13.04% of the nodes are out of control with a minimum voltage of 0.9035 p.u at node 65 [17]. The active and reactive losses are 238 kW and 106.5 kVAr respectively, and are more important in branches 4 and 5 and then in branches 56 and 57.

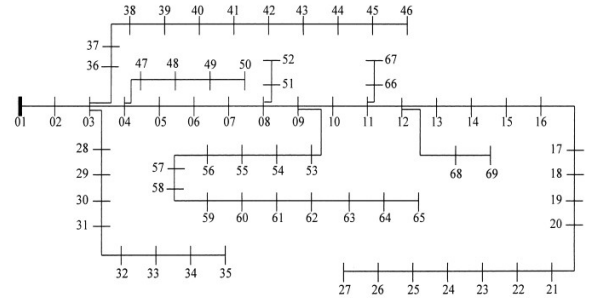


Fig.2. Diagram of the 69-bus IEEE network

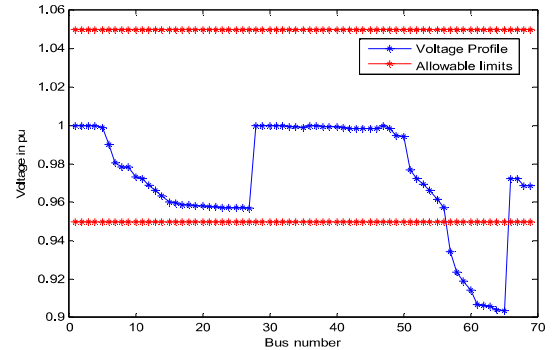


Fig. 3. Voltage profile of the IEEE network 69 bus.

1) Calculation of the Voltage Stability Indices of the IEEE 69-Bus Network : Table I shows the results of the calculation of the node stability indices applied to the 69-bus network. It is observed in this table that the lowest VSI are identified at nodes 64 (0.6663) and 63 (0.669); Index ENVCI (0.8163-0.817) and 0.821 for node 62, BVSI of 0.816(64), 0.816(63), 0.821(62) and 0.821 (61); VSF of 0.8992(60), 0.902(63) 0.903(64), 0.906(61). It is found that the most critical nodes are almost identical by VSI, ENVCI, and BVSI which is the new index proposed in this paper. It can then be deduced that the proposed new index is effective and efficient and can help operators quickly identify the most vulnerable nodes in a network for subsequent contingency planning. This

mathematically simple index can then allow network planners to quickly evaluate the voltage stability performance of their network in order to prevent potential vulnerabilities that could stress it and bring it down.

TABLE I. MAGNITUDE FOR WEAK BUS IDENTIFICATION BY EACH BUS INDEX (IEEE69BUS SYSTEM)

Bus	VSI	Bus	ENVCI	Bus	BVSI	Bus	VSF	Bus	L
64	0.6663	64	0.8163	64	0.816	60	0.899	56	0.0924
63	0.669	63	0.817	63	0.816	63	0.902	57	0.0471
62	0.674	62	0.821	62	0.821	64	0.903	6	0.0372
61	0.675	61	0.821	61	0.821	61	0.906	5	0.0355
60	0.679	60	0.822	60	0.819	26	0.957	60	0.0323
26	0.839	26	0.916	26	0.916	14	0.957		

Table II presents the results of the calculation of the line indices applied on the 69-bus network to identify the critical lines.

TABLE II. MAGNITUDE FOR CRITICAL BRANCH IDENTIFICATION BY EACH LINE INDEX (69 BUS SYSTEM).

Lines	FVSI	Lines	Lmn	Lines	LQP	Lines	LVSI
56-57	0.174	56-57	0.167	56-57	0.017	56-57	0.079
57-58	0.089	57-58	0.087	48-49	0.009	57-58	0.039
6-7	0.046	6-7	0.046	6-7	0.009	48-49	0.038
59-60	0.046	59-60	0.045	5-6	0.009	6-7	0.034
5-6	0.044	5-6	0.044	57-58	0.009	5-6	0.033
60-61	0.041	60-61	0.041	60-61	0.009	60-61	0.027
Lines	NLSI	Lines	VCPI				
56-57	0.092	56-57	0.022				
57-58	0.047	57-58	0.011				
6-7	0.037	6-7	0.009				
5-6	0.035	5-6	0.008				
60-61	0.032	60-61	0.007				

2) *Optimal Compensation of IEEE 69-Bus Network:* Table III shows the results of capacitor placement in the 69-bus network by the traditional node and line voltage stability indices and then the new BVSI index developed in this work. It is observed that the positioning by VSI and BVSI indicate the same node 64 to receive the same capacitor capacity of 1200 kVar. The losses, which were initially 238kW, were reduced to 168.3kW, an improvement of 29.8%. Regarding the positioning by the line indices FVSI and LQP, they identify the positioning on the same section 60-61 with an identical capacity of 2100kVar. The losses decreased to 186.5kW which is an improvement of 21.63% compared to the initial state and -9.75% compared to the state of the network after the placement by BVSI and VSI despite the 2100kVar power calculated by the algorithm. From these different results it can be deduced that the BVSI developed in this paper is reliable and can be validated to be applied to real distribution networks to identify their voltage vulnerability. It can also be concluded that node indices (VSI and BVSI) are more efficient, accurate and effective for optimal compensator placements than line indices.

TABLE.III. RESULTS COMPENSATION 69-BUS TEST SYSTEM BY EACH INDEX

Items	uncompensated	Compensated		Compensated	
		BVSI	VSI	FVSI	LQP
P_{loss} (kW)	238	168.3	168.3	186.5	186.5
reduction in P_{loss} %	0	29.28	29.28	21.63	21.63
V_{min} (pu)	0.9033	0.9273	0.9273	0.9331	0.9331
Unstable nodes	9	9	9	7	7
Optimal location		64	64	60-61	60-61
Total kVAr		1200	1200	2100	2100

Figure 4 shows the voltage profiles before and after compensation of the IEEE 69 bus network by the BVSI node index

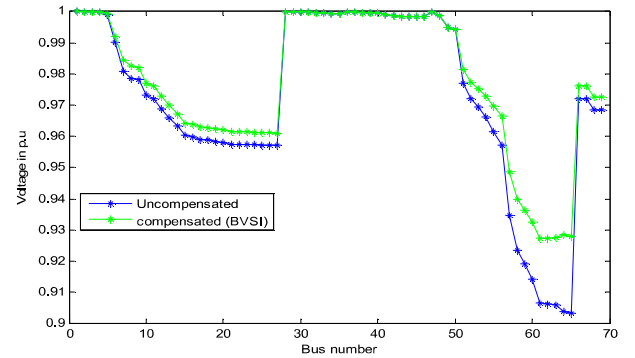


Fig.4. voltage profile improvement of 69-bus system

Table IV shows the results of this positioning optimization compared to references [1] and [18]. It is observed that the capacitor size evaluated is 1200kVar at node 64 while in reference [1] and [18], the authors have respectively sized capacitors at nodes 8, 58 and 60 which have a total power of 1800kVar and with a power of 1600kVar fragmented at nodes 59, 61 and 64. It can then be deduced that sizing the optimal compensator to improve the performance of the 69-bus network is more efficient and less expensive with BVSI than with the heuristic method in [1] and Fuzzy genetics used in [18]. This index can then be recommended to network operators to enable them to improve the efficiency of the identification and the solutions provided to perform their networks. The losses decreased from 238kW for the initial case to 168.3kW after compensation while in references [1] and [18], these losses are 148.48kW by the heuristic method and 156.62kW by the genetic algorithm method respectively. It is observed that the compensation by the methods used in [1] and [18] are more efficient than the BVSI that we have developed in this paper. However, the differences are relatively very small and it can be deduced from the reliability and validation of the BVSI.

TABLE IV. 69-BUS TEST SYSTEM PERFORMANCE ANALYSIS

Items	uncompensated	Compensated BVS	uncompensated	Compensated	
				Heuristic Method[1]	Fuzzy-GA [18]
P_{loss} (kW)	238	168.3	224.89	148.48	156.62
reduction in P_{loss} %	0	29.28	0	34	30.4
V_{min} (pu)	0.9033	0.9273	0.9091	0.9305	0.9369
Optimal location and size		64		8 1600	59 100
		1200		58 150	61 700
				60 1050	64 800
Total kVAr		1200		1800	1600

B. 123-Bus Ville-Madarounfa Distribution Network

Figure 5 shows the diagram of the study network. The two HV feeders Ville-Madarounfa of Maradi (Niger) constitute a real distribution system with an operating voltage of 20 kV. It is composed of 123 nodes.

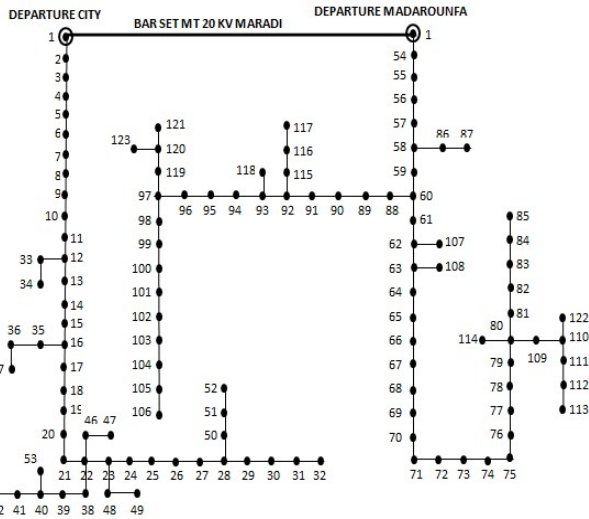


Fig.5. Single line diagram of the two 123Bus HV feeders

Figure 6 shows the voltage profiles following the power flow calculation of this network. It is observed that 72 nodes in this network are out of control and generate a minimum voltage of 0.8917pu at node 32. The active and reactive power losses are 614.2 kW and 309.9 kVAr. It is observed that several voltages are out of control. The receivers that are connected to these nodes are poorly powered and do not guarantee a quality of delivery that meets the requirements of EN 50160. The capacitors initially placed in the substation to regulate the voltages on the HV bus bars are not very efficient and most of them are no longer functional due to resonances and their inappropriate sizing. It is then necessary to resize and reposition the capacitors in this network, taking into account the new constraints, in particular the profile of the loads and their center of gravity which is very dynamic in the distribution networks. In practice, the center of gravity in a distribution network moves very quickly, taking into account the direction of the evolution of loads and the distributions that take place on the HV feeders.

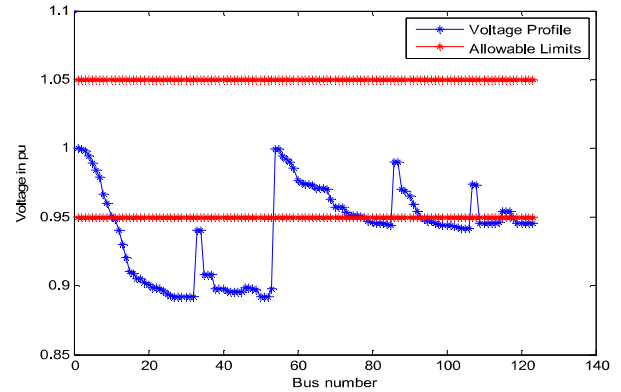


Fig .6. Voltage profile of the 123- bus network

1) Optimal Compensation of 123-Bus Network by the BVS: Based on the calculated BVS indices, it is indicated (Table V), the positioning of capacitors at node 31(2100kVar), 84(1050kVar) and 105 (2100kVar). Network losses decreased from 614.2 kW to 487 kW after compensation, a reduction of 20.7%. The minimum voltage increased from 0.8917pu to 0.9172 p.u and the number of unstable nodes decreased from 72 to 39. Moreover, with four capacitors positioned at nodes 31 (2100 KVar), 84 (1050kVar), 105 (2100kVar) and 51 (1200 KVar), it is observed that the losses have increased from 487 previously to 548.9, that is to say, an increase of 12.71%. The number of unstable nodes goes from 39 to 38, that is to say, a deterioration of 2.56%. On the other hand, the minimum voltage of the network has improved by 1.19%, but has always remained within the normative ranges. It can be deduced that this option, which tends to further increase the losses in the network, is not optimal for improving the performance of the Niger network. It is observed that despite the multiple compensation that the number of unstable nodes remains in a proportion of 31.70%. It can be concluded that even well positioned capacitors often fail to fully and efficiently compensate the reactive energy of a distribution network. It is then often recommended to combine compensation with other control techniques or to use FACTS devices which require high costs and a higher technicality of installation. Figure 7 shows the voltage profile on the bus before and after compensation.

TABLE V. RESULTS COMPENSATION 123-BUS VILLE-MADAROUNFA

Items	Uncompensated	Compensated BVS			
		481	487	548.9	548.9
P_{loss} (kW)	614.2	510.4	481	487	548.9
reduction in P_{loss} %	0	16.9	21.68	20.7	10.63
V_{min} (pu)	0.8917	0.9172	0.9172	0.9172	0.9282
Nodes Unstables	72	69	53	39	38
Optimal location and size		31 2100	31 2100	31 2100	31 2100
			84 1050	84 1050	84 1050
			105 2100	105 2100	105 2100
				51 1200	51 1200
Total kVAr		2100	3150	5250	6450

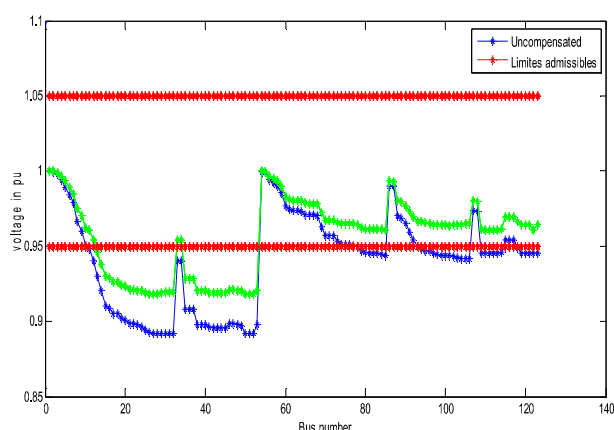


Fig.7. voltage profile improvement of 123-bus system

VI. CONCLUSION

The distribution networks in Maradi are in a state of near collapse. Several customers connected to this network are confronted with the poor quality of supply that is reserved for them. In this paper it was proposed a quick calculation index of the stability state (BVSI) that allowed to identify the impacting nodes that could receive compensators to the effect of improving this network. Three capacitors were positioned at optimal points, resulting in a 20.7% reduction in network losses and 31.70% of the nodes still remained within out-of-normative range. The change from three capacitors at three nodes to four capacitors at four nodes shows that the tendency to increase the number of capacitors in a network does not improve its technical performance much. It can be concluded that no matter how capacitors are positioned in the network, they are always limited in their effectiveness in improving the performance of an electrical system. The BVSI is an efficient, accurate and effective index to detect early the vulnerability of a distribution network in order to predict the first signs of voltage collapse, the effects of which are often catastrophic. It can be deduced that node indices are more accurate and are recommended to search for vulnerable points in distribution networks in order to improve their technical performance through compensation.

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