Impact of distributed capacitors on voltage profile and power losses in real low voltage distribution networks

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***Abstract*—Voltage control in low voltage distribution networks continues to remain an issue of significant importance. The large portion of long overhead lines with high R/X ratio has been the main reason that these circuits were suffering from constant voltage fluctuations problems, especially during heavy load time period. In this paper, the effect of introducing distributed capacitors as potential voltage regulation technique, in the voltage profile and power losses in low voltage radial systems was investigated. Two circuits were selected from the existent Norwegian low voltage distribution grid for a profound analysis of voltage problems. The circuits are of different size with different load demand. The assessment was conducted for maximum, 50% and minimum load condition. The load flow was performed for the steady state of the system. The perceived approach seeks to maintain the voltage within satisfactory limits by compensating for reactive power at load terminals. The low voltage radial circuits were modeled using MATLAB/Simulink software and the load flow problem was solved using Graphical User Interface (GUI) toolbox. The obtained results showed the good performance of distributed capacitors to improve the voltage profile in the system.**

Keywords*—LV Circuit, Voltage profile, Distributed Capacitors, MATLAB/Simulink, Load Flow.

NOMENCLATURE

AMI	Advanced Metering Infrastructure
EN	Eidsiva Nett AS
GUI	Graphical User Interface
LV	Low voltage
$OLTC$	On Load Tap Changer

I. INTRODUCTION

Electrical power has become progressively crucial especially with the great increase of substantial need for electricity due to the fast population growth and economic development. This power is normally delivered to the end users or who are commonly called consumers through high voltage transmission, sub-transmission, medium voltage distribution and low voltage circuits [1]. Generally, they can have underground and overhead construction with radial or ring scheme of connection [2]. The main objective of the distribution network is the increase of quality of electrical service while providing reliable high-quality supply and continuity by maintaining voltage within secure limits as set forth by international standard EN 50160 [3] and Norwegian regulation regarding the power supply in the electrical power system [4] for main voltage parameters. According to the EN 50160 standard [3] and the Norwegian regulation regarding the power supply in the electrical power system [4] the variations in the effective value of the voltage measured as an average within one minute, could not exceed the value of $\pm 10\%$ of the nominal voltage value. Additionally, permissible limits at the consumer point of common coupling in low and medium voltage systems under normal operating conditions are clearly stated in this standard. A poor management of distribution network can cause considerable voltage drops leading to an increase of current in the system, resulting in higher losses in lines and an excessive heat. Indeed, this can cause the destruction of different consumer devices [5]. The control and operation of distribution grid is therefore fundamental to be held in a desired level of fidelity at every moment of time [6].

In this paper, two radial circuits consist of a great number of overhead lines were analyzed. The impact of introducing capacitors in the voltage profile and power losses in these circuits was investigated. The paper is organized as follows. In section II a literature study is presented for better understanding of voltage problems in distribution networks. Section III describes the methodology of the study. A description of voltage regulation case studies is given in Section IV. Section V gives the concluding results from this work. A discussion is conducted in section VI accompanied with the final conclusions gained.

II. LITERATURE STUDY

In literature, there are several research works conducted for voltage and reactive power control in distribution networks. Many important reactive power compensation technologies were reviewed in [7] in regard to methods used for load compensation and voltage support in power systems. Various approaches including Evolutionary Computational Techniques like Genetic Algorithm [8], [9], Particle Swarm Optimization [10], then Heuristic Optimization Technique [11], PDIPM [12] and other designed algorithms [13] and Volt/Var Optimization engines [14] have been developed to enhance Volt/Var control and optimization in the smart distribution grids of the future. An investigation of reactive power flows control through capacitor banks in distribution and industrial networks was proposed by authors in [15]. Three cases were developed using zero, one and two compensators placed in medium voltage buses. The results of this study showed that the voltage profile was improved after the placement of capacitor banks along the feeders. Furthermore, the voltage profile and power factor improvement through capacitors installed in a 11 kV medium voltage feeder were investigated in [5]. The proposed method from authors aimed to show the good capacitor capability of maintaining the voltage within admissible limits. However, the authors have not investigated the effect of the voltage increase through capacitors in power losses in the system. An assessment of voltage regulation techniques such as On Load Tap Changer transformers (OLTC), capacitor banks and energy storage in LV systems was investigated by authors in [16]. Six LV feeders with different penetration of photovoltaic generation were analyzed. From the results obtained authors were able to conclude that OLTC transformers placed in the main bus are capable of controlling directly the voltage in the system. Furthermore, the storage devices can be efficiently used especially during peak time periods by injecting reactive power into the grid. Authors in [17] have conducted an analysis of R/X ratio effect in the voltage regulation of distribution networks by increasing the amount of reactive power injected into the grid. They were able to conclude that the improvement of voltage profile through reactive power injection in the distribution networks with low R/X ratio can be efficiently achieved, while is considered inefficient in distribution networks with high R/X ratio. Voltage control through load demand variation, transformer load tap changer and renewable energy integration was addressed in [18]. The latter was performed in an automated environment of the distribution network. Additionally, the proposed method for voltage control developed in real-time has made great effort to keep the voltage within secure limits. A research on voltage optimization using local data from smart meters in LV circuits was conducted by authors in [19]. 100 families have participated in this study where the Automated Demand-Response strategy of the Smart Grid is implemented. The goal of maintaining the voltage within the range of values specified by standards is achieved.

In this paper, a realistic approach for voltage improvement through integration of distributed capacitors in real low voltage distribution networks was developed. The amount of var compensation was calculated based on the reactive power consumption of the load. Furthermore, the approach taken presents an economical viable solution which can be easily implemented from Eidsiva Nett AS (EN) company.

III. METHODOLOGY

A. Description of the LV networks Topology

Two LV circuits were selected from current Norwegian low distribution grid for a profound analysis of voltage problems. The networks are named Nereng and Strandgata respectively. Consumer complaints about voltage fluctuations have been the main driver that these circuits were selected for further voltage investigation. Such circuits are modeled in MATLAB/Simulink software. The data for the lines, cables, transformers and loads were extracted from NETBAS software. Voltage analysis was conducted based on statistical load data from this tool. The circuits are of different number of consumers with different load size and demand operating under various load condition. The consumers are fed with power through a 11 kV/240 V residential transformer which is equipped with manual tap changer. The position of the transformer's tap changer is only changed at the mid-season time. Furthermore, the LV circuits are three-wire grounded wye circuits radially connected running at 230 V nominal voltage. The latter are composed of household, agriculture and office sector, with the major participation of household sector. The geographical maps of the LV circuits under study are given in Figure 1.

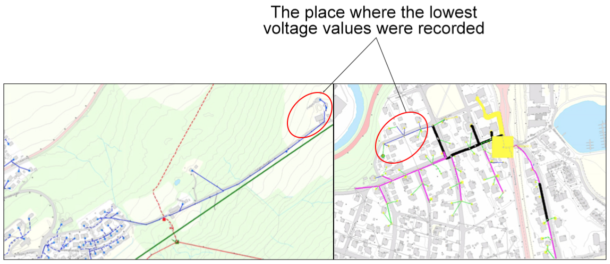
The place where the lowest
voltage values were recorded

Fig. 1: Geographical maps of the rural and urban LV circuits under study.

As a primary test network is taken a small LV residential circuit which delivers electricity to 9 houses by a Yyn0 100 kVA, 11 kV/240 V transformer. In Figure 2 is shown the single line diagram of the first LV circuit. The circuit is located in a rural area outside the town of Gjøvik. It consists of long lines with high R/X ratio and few loads. The total first circuit apparent power during the peak time period in January is estimated to be 74.9 kVA with a power factor of 0.97. The distance from the substation to the last consumer in the second output of the transformer is 0.7 km, while in the first output of the transformer is 0.29 km. The highest value of R/X ratio is estimated to be 1.11, while the lowest value is 0.08.

The second LV circuit is Strandgata circuit located within Gjøvik city. This is an old town circuit with overhead lines mostly. This circuit is fed by the Dyn11 800 kVA, 11 kV/240 V transformer. In the Figure 3 is shown the single line diagram of this circuit. The latter has 58 consumers in overall. The total apparent power is 519.07 kVA with a power factor of 0.97. This circuit consists of 58 consumers. The total length of the circuit is 3.72 km. The highest value of R/X ratio is 1.20, while the lowest one is 0.02. Consumers connected to the transformer output 7 were suffering from voltages drops. In the single line diagram the red color presents places where the voltage was lower than the specified limits. Almost all the consumers in these circuits are equipped with smart meters to monitor electricity consumption.

The main LV electrical grid characteristics are given in the Table I.

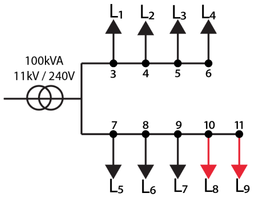

Fig. 2: Rural LV radial circuit single line diagram.

TABLE I: First LV electrical grid characteristics

Network type	Rural	Urban
Load consumer category	Residential	Residential
Number of consumers	9	58
Transformer rated power	100 kVA	800 kVA
Electrical grid topology	radial	radial
Total length of the grid	1.13 km	3.71 km

B. Network Model

The statistical load data are extracted from NETBAS software, and then used to create the model of LV circuits in MATLAB/Simulink. The yearly energy consumption for the last twelve months is known for every consumer. Based on that, the power is estimated as follows:

$$P_{max} = \frac{E(kWh/year)}{T(h/year)} \tag{1}$$

Where:

E is the total energy which was used in the last twelve months. T is Time of use" and T=3500h is a value given from Eidsiva Nett AS (EN).

The electricity surplus reaches the consumers through the transformer. The selected LV circuits are outputs of two winding transformer 11 kV/240 V. The two winding three-phase transformer models with the configuration Yyn0 and Dyn11, respectively were selected from Simulink Library. The lines and cables are modeled using RL branch model selected in the SIMULINK Library. The values for resistance and inductance of the lines and cables are extracted from NETBAS software and they are expressed in ohm. The loads are modeled as three-phase balanced loads. Considering that in the distribution systems, the loads are dependent on voltage, constant impedance (Constant Z) static load model was chosen for further analysis in the current model. Asymmetrical load flow problems were not considered in this study.

A load flow analysis which uses Newton-Raphson method was deployed in the three-phase system for running the simulations. The active and reactive power based on Newton-Raphson method are estimated as follows [20]:

$$P_k = \sum_{l=1}^{n} \mid V_k \mid\mid V_l \mid\mid Y_{kl} \mid \cos(\theta_{kl} - \delta_k + \delta_l) \tag{2}$$

$$Q_k = -\sum_{l=1}^{n} \mid V_k \mid\mid V_l \mid\mid Y_{kl} \mid \sin(\theta_{kl} - \delta_k + \delta_l) \tag{3}$$

The high voltage distribution grid was modeled as a three-phase source with a swing bus type selected in the load flow block. A load flow report gives the data for active and reactive powers, voltage magnitude and voltage angle at each bus of the system. The total active and reactive power losses in the system were also extracted from load flow report in MATLAB/Simulink. The Simulink model of the circuits as well as voltage, active and reactive power values were almost the same with the corresponding values obtained from NETBAS software.

C. Distributed capacitors

The distributed capacitors were used for reactive power compensation in this study. They have been placed in different buses, to see their effect in the voltage profile along the LV circuits. The analysis with capacitors placed in such circuits was carried out for maximum load condition. The capacitors were connected in delta configuration. The capacitor size was calculated based on the reactive power consumption of each load. In the condition of 50 % and minimum load, there is no need for capacitor placement because all the voltage values at every point of the grid are within specified limits. The size of capacitors was calculated as follows:

$$X_{cph} = \frac{V_{ph}^2}{Q_{cph}} \quad and \quad C = \frac{1}{X_{cph} 2\pi f} \tag{4}$$

Where:

X_{cph} is the capacitor reactance per phase expressed in (Ohm)

V_{ph} is the phase to phase voltage expressed in (Volt)

Q_{cph} is the reactive power per phase expressed in (kVAr)

C is the capacitor capacitance expressesed in (Farad)

IV. VOLTAGE REGULATION CASE STUDIES

A. Case 1

In case 1, the actual LV circuits were analyzed. The existing LV circuits without capacitors installed were studied for maximum, 50% and minimum load condition.

B. Case 2

In this case, voltage regulation in the LV circuits through the integration of distributed capacitors was analyzed. Capacitors were placed on every bus of the rural and urban LV circuits, respectively. The reactive power compensation through capacitors is conducted at each load at the same time. The size of capacitors was calculated based on the reactive power consumption of the load. Total reactive power compensated from capacitors in the rural LV circuit was 16.101 kVAr. The corresponding value in the urban LV circuit was estimated to be 121.324 kVAr. Voltage magnitude and active

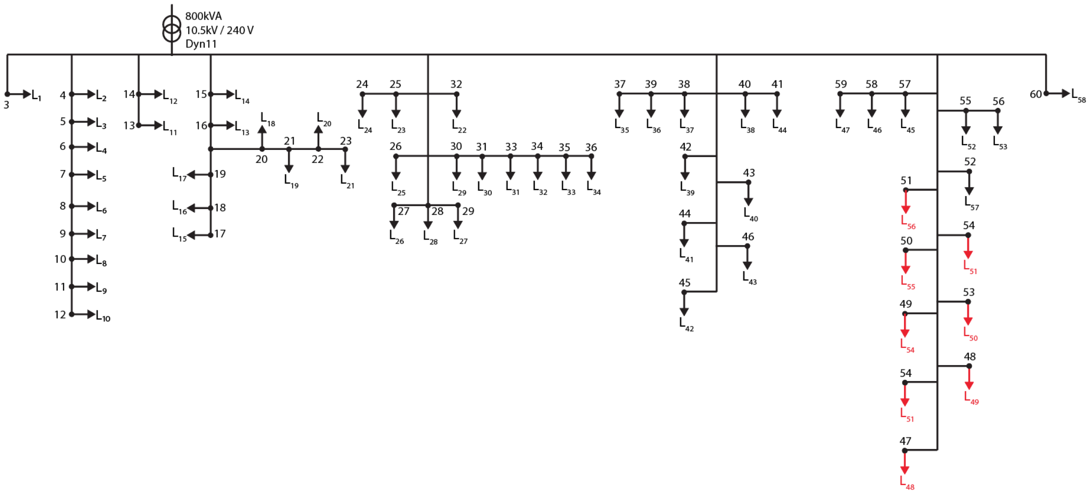

Fig. 3: Urban LV radial circuit single line diagram.

and reactive power losses in the system were the parameters investigated. The description of the case 2 is given in the Table II.

TABLE II: Case 2 description

	Bus No.	Total Reactive Power compensated (kVAr)
Rural LV circuit	All buses	16.11
Urban LV circuit	All buses	121.324

C. Case 3

An investigation of the placement of capacitors in the buses of the rural and urban LV circuits where the voltage values during maximum load condition were recorded to be very low was conducted in this case. In the rural LV circuit capacitors were placed at buses 9, 10 and 11 at the same time. In the second circuit, the voltage regulation is accomplished by putting capacitors on the critical buses, where the voltage values have violated the limits set forth by standards. The critical buses are bus 48, 47, 49, 50, 51, 53 and bus 54. This case was developed in 5 different scenarios. First, the size of the capacitors was calculated based on the reactive power consumption of the load, then this value was increased from two times up two five times increase in the capacitor size in the fifth scenario. The taken approach aims to see the effect of the increase of reactive power compensated through capacitors in the voltage magnitude and power losses in the system. The description of the case 3 is given in the Table III.

TABLE III: Case 3 description

	Bus No	Total Reactive Power compensated (kVAr)				
		Sc. 1	Sc. 2	Sc. 3	Sc. 4	Sc. 5
Rural LV Circuit	9, 10, 11	6.024	12.048	18.072	24.096	30.12
Urban LV Circuit	48, 47, 49, 50, 51, 53, 54	12.67	25.34	38.01	50.68	63.35

V. RESULTS

A. Case 1

Load profile in rural and urban LV circuits is shown in Figure 4. The total amount of active power that comes from high voltage distribution grid is 75.06 kW and 648.67 kW for rural and urban LV circuits respectively. This amount of power is used to supply the loads with power and to cover the active power losses in the circuits. Voltage magnitude in rural and urban LV circuits with no capacitors placed in the systems under the condition of maximum, 50% and minimum load is presented in the Figure 5. The lowest voltage value of 0.875 pu during the condition of maximum load in the rural LV circuit was recorded at bus 11 in the second output from the transformer showed in the single line diagram in the Figure 2. In the urban LV circuit, during maximum load condition, the voltage values in the output 7 of the transformer have violated the limited values. The lowest value estimated was 0.8329 pu. Furthermore, in the single line diagram in the Figure 3 the red color presents buses which were suffering from voltage drops problems. The 50% and minimum load condition are characterized by relatively good voltage profile in both circuits. The active power profile within a 24h for a typical January, April, August and September day for the most critical bus regarding voltage in both rural and urban LV circuits is shown in the Figure 6. In the bus 11 of the rural LV circuit the highest active power value of 16.16 kW was recorded at 10 AM on a typical January day, while the lowest value of 4.92 kW on August day at around 3 o'clock after midnight. The active and reactive power variations within 24h, for different seasons, was shown for the bus 48 in the urban LV circuit. This is the critical bus of the system where the lowest voltage value of 0.8329 pu in a January day was recorded.

B. Case 2

The impact of distributed capacitors in the voltage profile and power flows in the LV circuits under study was investigated in this case. The capacitors were placed in every bus at load terminals. In the Figure 7 the voltage profile along the rural and urban LV circuits with and without integration of capacitors is

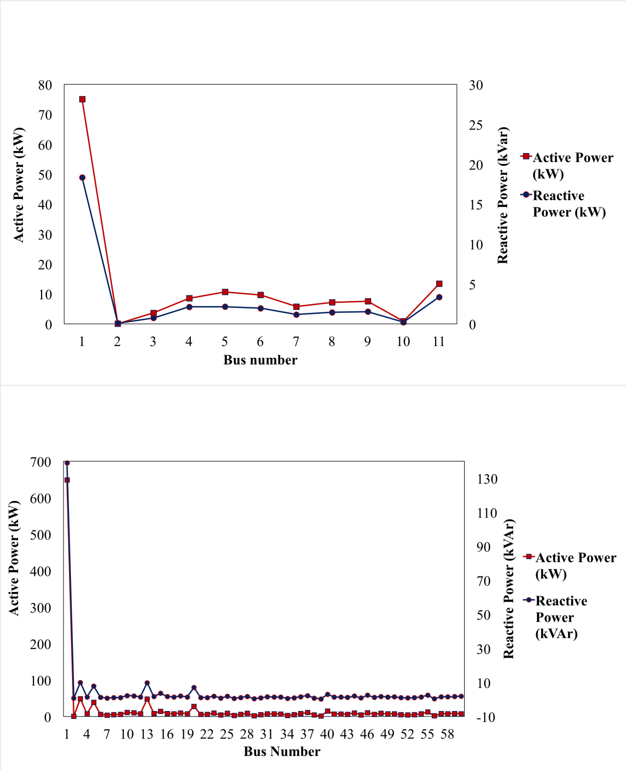

Fig. 4: Load profile in rural and urban LV circuits.

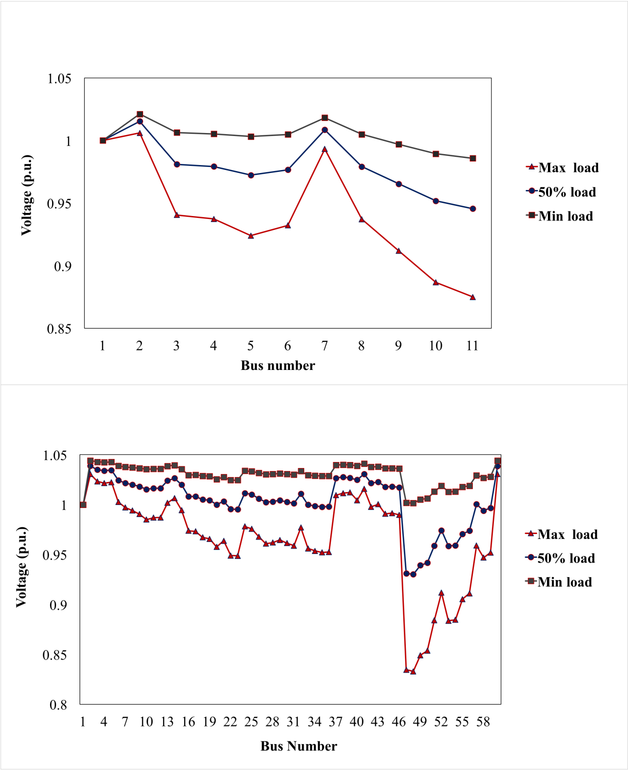

Fig. 5: Voltage magnitude in rural and urban LV circuits with no capacitors placed under condition of maximum, 50% and minimum load.

shown. In the rural LV circuit the lowest voltage value without the integration of capacitors was 0.875 pu. After the integration of capacitors at all buses, the lowest voltage value in the system was 0.893 pu. The corresponding value in the urban LV circuit during maximum load condition was 0.8329 pu at bus 48. After the placement of capacitors at all buses the lowest voltage value in the system was 0.8417 pu. A greater voltage improvement through distributed capacitors was observed in the most critical buses of the circuits where the voltage values were very low when compared to the other voltage values in the system. In the Figure 8 is presented active and reactive power profile in the rural and urban LV circuits. The bus 1 is the bus where the transformer is connected. The amount of active and reactive power that comes from the main high voltage distribution grid is then delivered through this bus to the loads connected to the low voltage systems. As it can be seen from Figure 8, the reactive power was completely compensated at every bus in both circuits. The active power profile remains to be almost the same from the actual active power profile. The values for active and reactive power as well as for voltage magnitudes at each load are extracted from the load flow report in MATLAB/Simulink.

C. Case 3

The behavior of the LV circuits with the integration of distributed capacitors was investigated in this case. The capacitors were connected in the most critical buses of the studied circuits at load terminals. The critical buses in the rural LV circuit are buses 9, 10 and 11. The corresponding buses for the urban LV circuit are bus 48, 47, 49, 50, 51, 53 and bus 54. These buses have been suffering from relatively low voltage values during maximum load condition. Voltage profile with and without integration of capacitors in the critical buses of the systems under study is shown in Figure 9. Five scenarios were developed within this case. The size of capacitors was increased in each scenario based on the increase of the reactive power injected into the particular bus. The increase of voltage at critical buses from the base scenario to the fifth scenario was 9%, with an increase in each scenario equal to 1.8%. Regarding the urban LV circuit, the increase in each scenario was equal to around 1%. The total increase from scenario base to scenario 5 was around 4%. The greater voltage increase it can be observed in the buses where lower voltage values were recorded. With the placement of the capacitors in the rural LV circuit, all the voltage values in the system are within specified limits. On the other hand in the urban LV circuit, the voltage in the bus 47, 48, 49 and 50 was increased, but additional increase needs to be performed if the objective for maintaining voltage values within limits stated in the standard during maximum load condition to be fulfilled. Due to the large number of buses in the urban LV circuit, the voltage profile in Figure 9 was only presented for the critical buses where the distributed capacitors were integrated. In addition, the voltage profile in the other buses of the system where satisfied voltage values were recorded remains almost the same with the values taken after the integration of distributed capacitors in the critical buses of the system.

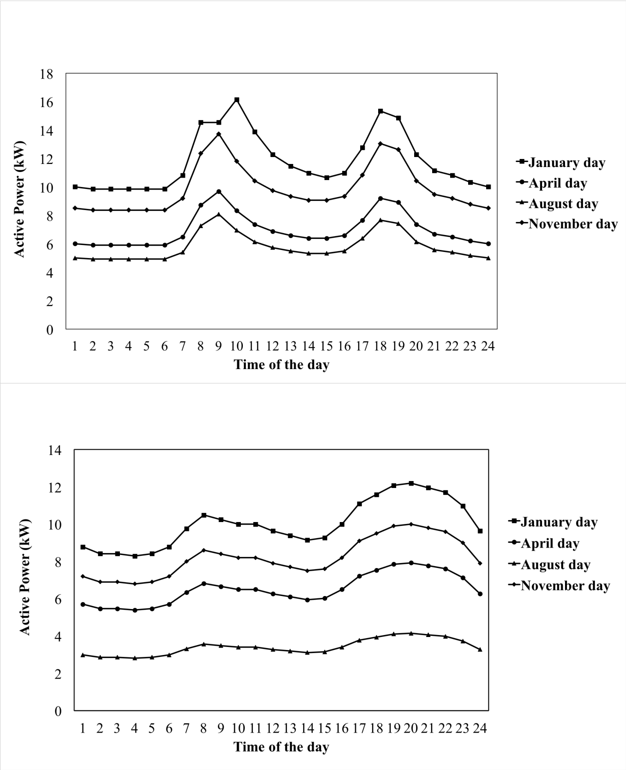

Fig. 6: Active power variation within 24h for a typical January, April, August and November day at the last critical bus 11 and 48 in the rural and urban LV circuits respectively.

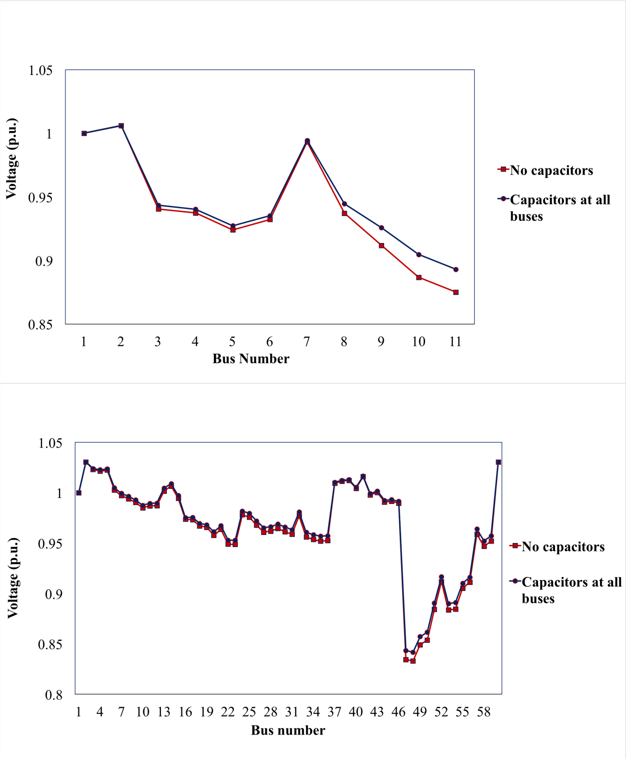

Fig. 7: Voltage magnitude in rural and urban LV circuits with and without integration of capacitors at all buses (case 2).

D. Power losses

A comparative study of the cases developed regarding the power losses versus voltage profile for both rural and urban LV circuits is conducted in this section. Active and reactive power losses for case 1, case 2 and case 3 are shown in Table IV.

TABLE IV: Power losses

		Rural LV Circuit		Urban LV Circuit	
		Active Power losses (kW)	Reactive Power losses (kVAr)	Active Power losses (kW)	Reactive Power losses (kVAr)
Case 1		7.15	3.29	44.73	12
Case 2		6.95	3.22	43.51	11.67
Case 3	Sc. 1	7.09	3.25	44.37	11.90
	Sc. 2	7.30	3.42	44.66	11.99
	Sc. 3	7.83	3.85	47.61	12.26
	Sc. 4	8.69	4.55	47.02	12.66
	Sc. 5	9.91	5.54	49.59	13.39

Both active and reactive power losses are reduced from case 1 to case 2 and in the first scenario of the case 3. In the latter cases, the load reactive power was compensated completely through the integration of capacitors at load terminals. In the case 3 five scenarios were developed while increasing the size of the capacitors that are connected at load terminals. First, the size of the capacitors was calculated based on the reactive power consumption of the load, then the size of capacitors was increased from two times up to five times. The taken approach aims to see the effect of the increase of the amount of the reactive power compensated at the particular load in the voltage magnitude and power losses in the system. The scenarios were performed for the case 3 when the capacitors were integrated at critical buses of the systems. The voltage increase due the increase of reactive power injected through distributed capacitors in the critical buses versus total active and reactive power losses in the system is shown in the Figure 10. With the increase of capacitor size (the reactive power compensated) the voltage profile is improved. On the other hand, a slight increase of the active and reactive power losses can be observed. For an increase of the voltage from 0.875 pu to 0.9553 pu in the bus 11 of the rural LV circuit, the total active and reactive power losses in the system are being increased for around 3 kW and 2 kVAr respectively. The rural LV circuit, was modeled in PSS/E software as well, and the results were almost the same. A higher amount of reactive power compensated compared to the reactive power consumption of a particular load will indeed led to an increase of voltage accompanied with a slight increase of power losses due to the potential increase of currents flowing in that part of the grid.

VI. CONCLUSION AND DISCUSSION

The need for maintaining the voltage profile within admissible tolerances is the main driver of the substantial increase of reactive power compensation devices in the distribution networks. A realistic approach for voltage improvement through integration of distributed capacitors in real low voltage distribution networks was developed in this paper. Two real LV radial circuits have been modeled in MATLAB/Simulink

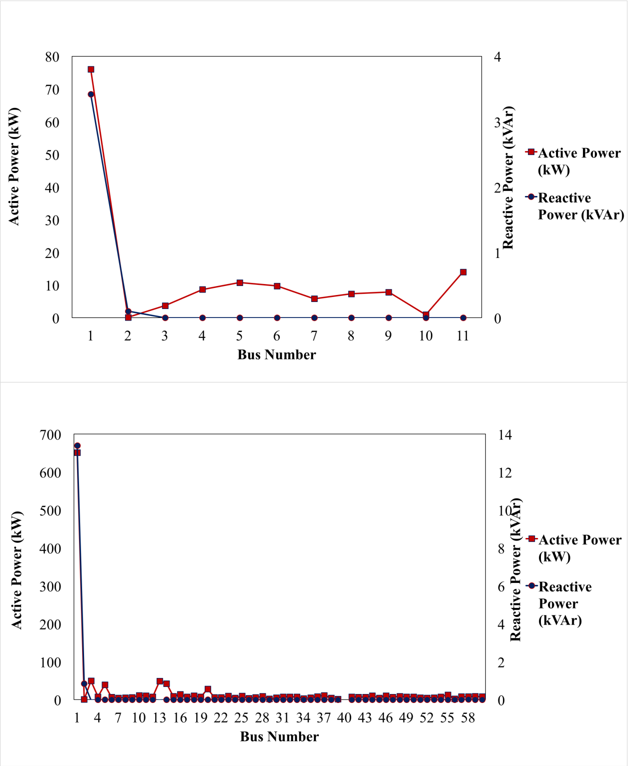

Fig. 8: Active and reactive power profile in rural and urban LV circuits with the integration of capacitors at all buses (case 2).

and a voltage and power flow analysis was carried out. In the LV circuits under study, voltage drops were detected mainly in the end part of the networks due to the large portion of overhead lines and heavy load. An assessment of the distributed capacitors effect in voltage profile and power losses in the LV distribution system is carefully considered and investigated. The placement of capacitors at all load buses of the system has increased the voltage for 2%. The double increase of capacitor size has led to a voltage increase of 4 %. Furthermore, a five-time increase of the capacitor size has led to around 9% increase of the voltage at the critical buses at load terminals. Lower percentage increase it can be observed for the urban LV circuit. The active and reactive power losses are reduced from case 1 to case 2 and in the first scenario of the case 3. On the other hand, a slight increase of the power losses was observed with the further increase of the reactive power compensated at load terminals. From the results obtained, it is concluded that the integration of distributed capacitors for reactive power compensation in low distribution system could improve relatively good the voltage profile in the system. Furthermore, integration of capacitors to mitigate undervoltage problems may be a better solution for some LV circuits. Building a new line or a new cable could possibly be more costly. An economical viable solution through the developed method can be easily implemented from Eidsiva Nett AS (EN) company. The addressed approach for voltage improvement through distributed capacitors in this paper was analyzed for maximum load condition. It should be emphasized that, during light load (summer time) the distributed capacitors must be

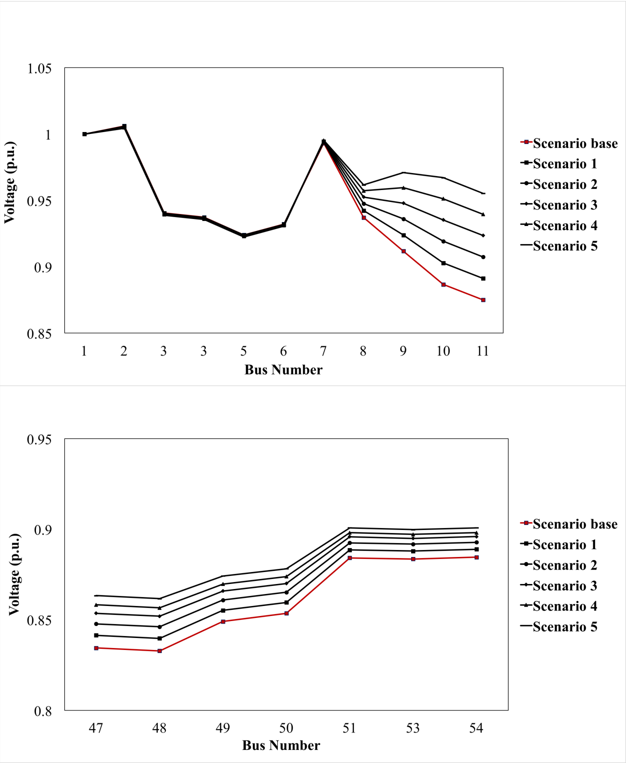

Fig. 9: Voltage magnitude in rural and urban LV circuits with and without integration of capacitors (case 3).

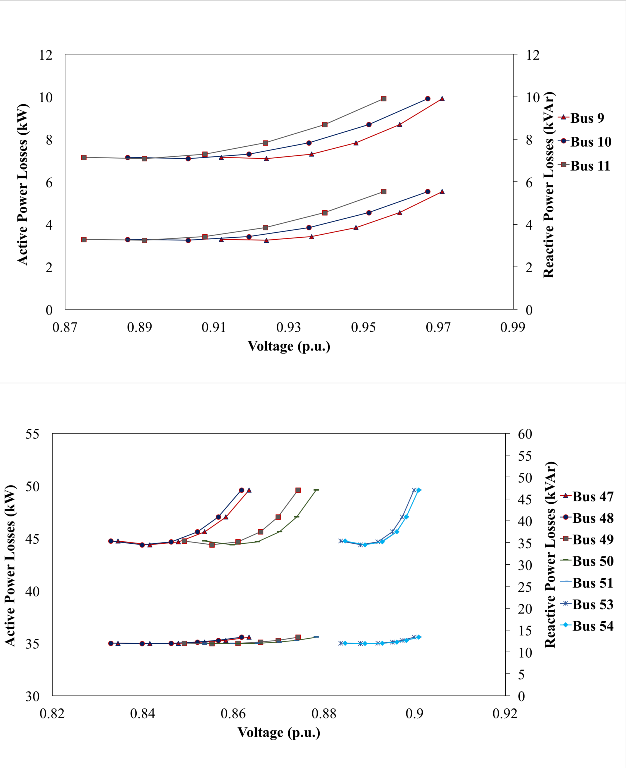

Fig. 10: Voltage versus active and reactive power losses in the system for different scenarios developed in case 3.

switched in the turn off mode, due to high voltage values that are likely to occur in the critical parts of the studied circuits.

The method used in this paper does not include optimization or any smart technique for voltage and reactive power control, due to the lack of data from Advanced Metering Infrastructure (AMI) system in the time when the study was performed. However, the future work arising from the current study will deal with additional improvement of voltage profile and considerable power loss reduction achieved through a real-time or quasi real-time optimization of the LV network designed and performed carefully within the future smart grid environment. The measurements conducted in the actual paper can be used as input for the future work.

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