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Voltage Profile Improvement & Loss Reduction using Optimal Capacitor Placement

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***Abstract:** Electricity is very essential requirement for our day to day life. Electricity comes to us from the power generating stations through power transmission & distribution networks. The load centres or the consumers are at the last stage of power transmission. For the stable operation of this complete system, it is essential that the system should operate reliably under all circumstances. As the power system is a non-linear & complex system, there occur many problems especially in electrical distribution systems like voltage sag or poor voltage profile, high reactive power demand, change in the reactive power demand with change in loading category etcetera. Under the effect of these problems the voltage instability becomes the frequent phenomena. So for the system to operate in voltage stable state, the problems which disturb the voltage stability should be eliminated or compensated. In this paper a 20 MVA, 10 distribution feeder electrical radial distribution system is assumed for the voltage stability analysis in ETAP software and its voltage profile is improved using optimal switched capacitor placement. The switched capacitors are placed at low voltage side of distribution transformers starting from the first marginally unstable node. The size of capacitor is determined from the reactive power demand by the system loads at different loading categories.*

***Keywords:** Voltage Stability Analysis, Voltage Profile Improvement, Optimal Capacitor Placement, Reactive Power Management.*

I. INTRODUCTION

Electrical energy is one of the very essential necessities for our daily life. So the maintenance of power quality in the power system networks is very important. The power systems are non-linear and complex systems, so it is required that they should operate in stable state under all circumstances. But today's power systems are facing many problems in their regular operation like voltage sag in distribution systems, poor voltage profile, high reactive power demand by the load, change in reactive power with change in loading category or load demand etcetera. These problems obstruct the regular or intended operation of the power systems. Under such scenario the voltage instability becomes the frequent phenomena especially in the electrical power distribution systems.

The voltage stability analysis, in the present scenario, has become the emerging topic in the field of research in electrical power system world. In the past few years, many contributions to a better knowledge of various aspects of voltage instability problem have been reported in the literature, where the problem has been explored from the various levels of abstraction. Voltage instability is considered to be one of the main threats to the power system stability, security and reliability. This is due to the reason that many electrical power system blackouts, in the past, were caused mainly due to voltage instability phenomena or voltage limit violations in the system network [5].

In the voltage stability analysis, the main focus is towards finding the maximum loadability of the system network and causes for the voltage instability. Voltage instability phenomena generally occur with the system over loading and high reactive power demand by the load centres. In the voltage instability phenomena the voltage profile of the system becomes poor along the length of the power line and reactive power demand by the load centres becomes high. Voltage instability, in some studies, is considered as inability of the system to provide sufficient reactive power with the load variations, especially at the weak nodes of the system. Therefore for a stable system, it is very important to regulate reactive power requirement in the system with load variations. There is a direct link between the consumption of reactive power in the system and the system voltage. Also there should be no over compensation for reactive power requirement. So to maintain the voltage stability reactive power must be properly controlled, there should be no mismatch between reactive power generation and consumption in the system [11]. Hence, the voltage stability puts some restrictions on the power system operation [3].

In the phenomena of voltage instability, the electrical load characteristics have a very crucial effect on the voltage stability of the electrical system [4]. As the nature of the power flow depends upon the nature of the system loads, the analysis of system loads helps in the voltage stability analysis in a better way [8]. The system loads or the system load characteristics can be analysed using load flow analysis of the whole system. The load flow analysis of the system gives the details about system's voltage profile, causes of voltage instability and values of power flows at various system branches [7], [12], [13]. The knowledge of reactive power flow at various system branches is essential for sizing the reactive power compensation devices like sizing of static capacitors. In a practical system, especially the Indian electrical distribution system, the load demand and load characteristics are constantly changing on the per hour basis in its daily operation. So the load flow analysis should be performed for different loading categories or according to the system's load duration curve [18]. With the change in load demand and load nature, the reactive power demand by the load is also changing respectively. Hence, for the proper reactive power compensation, the reactive power demand should constantly meet as per the load requirements.

The resistance and reactance of the electrical power lines has also contribution in the voltage instability phenomena. This is because the resistance and reactance of electrical power lines is also responsible for voltage drop along the length of power lines. This also reduces the power transfer capability of the lines and increases the electrical power loss. The resistance and reactance of power lines becomes the addictive factors for voltage instability when the reactive power demand by the system is high. The voltage instability problem becomes critical in the case when reactive power demand of the system increases beyond the sustainable capacity of the transmission system [1].

The above discussed factors become additive in case of practical electrical distribution systems, where the basic requirements are of proper voltage, sufficient reactive power reserve with load variation, availability of power demand and reliability. In practical distribution system networks most of the load is inductive in nature and hence the system voltage gets dropped along the length of the line. Generally the bus or node voltage at far ends of the system is much lower than the near ends. Theses weak nodes in the system become the supporting reasons for the voltage collapse. The identification of the weak nodes or buses in the system is very crucial in voltage stability analysis.

It is a common practice to use the capacitors for improving the voltage profile of an electrical system. The other advantage of installing capacitors is they help to reduce system losses by improving the power factor of the electric system. Capacitors can be installed for both conventional and unbalanced loading categories [9]. The main point of interest in optimal capacitor placement is the optimal allocation of the capacitors to reduce the overall cost of capacitor installation [2] and their size detection. There are many techniques and methods for the optimal placement and sizing of capacitors. In a study conducted on 15, 69 and 118 radial electrical bus systems the capacitors were optimally placed and their optimum size was detected using flower pollination optimization algorithm [16]. In an another study, conducted on IEEE 34 and IEEE 118 bus system, voltage profile of the system was improved using shark smell optimization [15]. Similarly in some other studies the use of firefly algorithm, PSO technique, gravitational search algorithm was made for optimal placement and sizing of capacitors [1], [2], [10], [11], [14], [15]. However such systems are non-realistic in nature because the practical electrical systems are much larger systems and will include larger number of buses. Also, in these studies, because of small systems, the effect of voltage profile deterioration along the length of power line is not considered in optimal capacitor placement. Hence these studies are not valid for the practical systems, especially the Indian electrical distribution systems.

In this paper, the voltage stability analysis is performed on an assumed radial electrical distribution network using ETAP software. The weak nodes in the system are found using load flow analysis and the voltage profile of the assumed system is improved using optimal placement of switched capacitors on the low voltage side of distribution transformers.

II. PROBLEM FORMULATION

From the analysis of the various literatures on the voltage stability studies, it is found that most of the studies are done using standard bus systems and balanced loads on small systems that are impractical especially for Indian distribution systems [1] – [18]. In practical electrical power system, the load is generally of imbalance type especially in domestic supply systems and there are the loads of different loading category that are fed by the same distribution substation. In a practical distribution network there is larger number of distribution transformers feeding the loads of a different nature at different places along the distribution line. Under this condition, the voltage profile of a power line is deteriorated along its length. Hence there is a need to consider the effect of nature of loads along the length of power lines.

The electrical conductors, distribution transformers and other such electrical equipment are exposed to physical conditions of the region in which they are installed. There is a need to model the physical conditions along with the electrical parameters of the system. In some cases, the effects of physical conditions of the region de-rate the rating of electrical equipment especially in case of resistance of power line conductors.

By considering this scenario, the role of physical conditions and nature of load along the length of power line should be considered for voltage stability analysis. Hence, it is required to model an electrical system by considering the role of physical conditions of the region of installation and nature of load along the length of power lines to get more accurate results on voltage stability analysis. For this purpose, a practical distribution system or a very similar system to practical distribution system should be considered and its model should be made in any standard simulation software for voltage stability analysis.

For the electrical power system simulations, ETAP is the most reliable and widely used software. In this paper, all the work related to voltage stability analysis is done in ETAP software.

The objectives of this research work are as follows:

- To model the assumed radial electrical distribution system in ETAP software.

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- To perform the load flow analysis on the modelled system in ETAP software.
- To identify the weak nodes or buses of the modelled electrical distribution system.
- To optimally install the capacitors for improving voltage profile of the modelled system and loss reduction.

III. PROBLEM MODELLING

In this paper, a 20 MVA electrical distribution system with 10 electrical feeders is assumed for voltage stability analysis. The system is assumed to be static as an electrical grid is assumed to be the source of electrical power. The complete assumed system is modelled as single line diagram in ETAP software. The supply feeder system is assumed to be consisting of 8 agricultural feeders with conventional loading category, one feeder is assumed to be Industrial with conventional loading category and one feeder is assumed to be domestic feeder with imbalance loading category. One small region C1 is given supply from the industrial supply feeder C. The feeders E and F are assumed to have a common circuit breaker. Similarly feeders G and H are assumed to have common circuit brakers. The electrical distribution substation is assumed to have one 100 kVA in-house transformer for substation power supply usage. There is assumed to be one battery charger for charging substation's battery house. The assumed specification for the battery house is shown in the table 1.

Table I. Assumed Specification of Battery House

S. N.	Specification	Value
1	Manufacturer	C & D Tech
2	Number of Cells	110
3	Rated Open Circuited Voltage	226.9
4	Total Capacity	1200 AH

The assumed specification of the battery charger is shown in the table 2.

Table III. Assumed Specification of Battery Charger

S. N.	Specification	Value
1	Power Rating	10 kVA
2	Rated Voltage	0.415 kV
3	Power Factor	0.95
4	Efficiency	90%
5	DC Rating	8.55 kW, 220 V, 38.86 A

These assumptions make the assumed system to be similar to practical electrical distribution system as in Indian electrical supply distribution systems. The modelled system in ETAP software is shown by the Fig. 1.

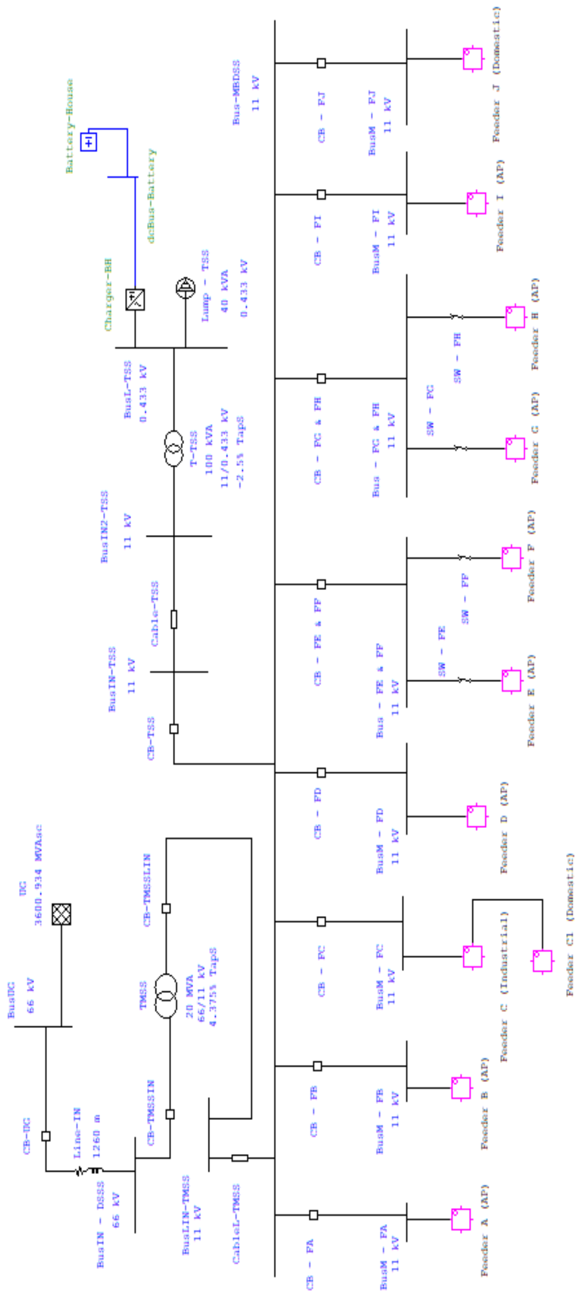

Fig. 1. Modelled Assumed Electrical Network in ETAP

The assumed specification of 20 MVA power transformer is shown in the table 3.

Table IIIII. Assumed Specification of Power Transformer

S. N.	Specification	Value
1	Power Rating	20 MVA
2	Voltage Rating (Primary/Secondary)	66/11 kV
3	Type/Sub-Type	Liquid-Fill/Mineral

		Oil
4	Class	ONAN
5	Altitude (Installation)	650 ft
6	Temperature Rise	65 ℃
7	Grounding (Primary/Secondary)	Both in Star with Solid type
8	Vector Group	YNyn0
9	Basic Insulation Level (Primary/Secondary)	325/75 kV
10	Harmonic Data Standard	G2/3P-FL_LL with K Factor = 9
11	Magnetization Inrush	Point Type with Multiplier 6 and 40 Cycles

It is assumed that the specification of all the distribution transformers are same, the only difference is in their power ratings. The assumed specification for distribution transformer is shown by the table 4.

Table IVV. Assumed Specification for Distribution Transformer

S. N.	Specification	Value
1.	Power Rating	According to Installation
2.	Voltage Rating (Primary/Secondary)	11 kV/433 V
3.	Type/Sub-Type	Liquid-Fill/Mineral Oil
4.	Class	ONAN
5.	Altitude (Installation)	650 ft
6.	Temperature Rise	65 ℃
7.	Grounding (Primary/Secondary)	Both in Star with Solid type
8.	Vector Group	YNyn11
9.	Basic Insulation Level	75 kV
10.	Harmonic Data Standard	G2/3P-FL_LL with K Factor = 9
11.	Magnetization Inrush	Point Type with Multiplier 9 and 40 Cycles

The same type of conductor is assumed to be used everywhere in the modelling of this assumed electrical distribution system. The average distance between one transformer to other transformer is assumed to be of 250 meters and the average distance between the feeder and first transformer of that feeder is assumed to be of 560 meters. The specification of the assumed transmission line conductor is shown in table 5.

Table V. Assumed Specification of Power Lines

S. N.	Specification	Value
1	Conductor Code	APPLE 1120
2	Conductor Type	ACSR
3	Conductor Name	Pirelli-AACSR/GZ
4	Phase Configuration	Triangular
5	Phase Height	24.606 ft
6	Conductor Spacing (AB,BC,CA)	2.762 ft, 2.762 ft, 3.51 ft
7	Conductor GMD	2.992 ft
8	Number of Ground Wires	0
9	Horizontal Tension	2280 lb
10	Wind Force	0.386 lb/ft^2
11	K Factor	0.3 lb/ft^2
12	Operating Temperature	35 ℃
13	Loaded Conditions (K Factor, Wind Loading)	0.05 lb/ft, 0.73 lb/ft^2
14	Wind Speed, Wind Direction	18ft/s, 45 Degrees
15	Installation Elevation	624.6 ft
16	Installation Azimuth, North Latitude	0, 30.7 Degree
17	Solar Absorbtivity, Emissivity	0.5, 0.6

The system loads, connected to the secondary winding of all distribution transformers, are modelled as lumped loads and assumed to be of the same power rating as the distribution transformer to which they are connected. The power factor of all the system loads assumed in the range of 0.85 to 0.88 for agricultural feeders and for industrial and domestic loads it is assumed to be in the range of 0.88 to 0.95.

The number of distribution transformers installed in feeder A is shown in table 6.

Table VI. Number of Distribution Transformers in Feeder A

S. No.	Transformer Rating	Number of Transformers
1	16 kVA	9
2	25 kVA	18
3	63 kVA	6
4	100 kVA	5

The number of distribution transformers installed in feeder B is shown in table 7.

Table VII. Number of Distribution Transformers in Feeder B

S. No.	Transformer Rating	Number of Transformers
1	16 kVA	8
2	25 kVA	10
3	63 kVA	11
4	100 kVA	6

The number of distribution transformers installed in feeder C is shown in table 8.

Table VIII. Number of Distribution Transformers in Feeder C

S. No.	Transformer Rating	Number of Transformers
1	16 kVA	3
2	25 kVA	4
3	63 kVA	1
4	100 kVA	27

The number of distribution transformers installed in feeder D is shown in table 9.

Table IX. Number of Distribution Transformers in Feeder D

S. No.	Transformer Rating	Number of Transformers
1	16 kVA	15
2	25 kVA	13
3	63 kVA	11
4	100 kVA	6

The number of distribution transformers installed in feeder E is shown in table 10.

Table X. Number of Distribution Transformers in Feeder E

S. No.	Transformer Rating	Number of Transformers
1	16 kVA	18
2	25 kVA	15
3	63 kVA	7
4	100 kVA	6

The number of distribution transformers installed in feeder F is shown in table 11.

Table XI. Number of Distribution Transformers in Feeder F

S. No.	Transformer Rating	Number of Transformers
1	16 kVA	4
2	25 kVA	20
3	63 kVA	12
4	100 kVA	8

The number of distribution transformers installed in feeder G is shown in table 12.

Table XII. Number of Distribution Transformers in Feeder G

S. No.	Transformer Rating	Number of Transformers
1	16 kVA	6
2	25 kVA	13
3	63 kVA	14
4	100 kVA	9

The number of distribution transformers installed in feeder H is shown in table 13.

Table XIII. Number of Distribution Transformers in Feeder H

S. No.	Transformer Rating	Number of Transformers
1	16 kVA	5
2	25 kVA	12
3	63 kVA	12
4	100 kVA	5

The number of distribution transformers installed in feeder I is shown in table 14.

Table XIV. Number of Distribution Transformers in Feeder I

S. No.	Transformer Rating	Number of Transformers
1	16 kVA	2
2	25 kVA	16
3	63 kVA	10
4	100 kVA	14

The number of distribution transformers installed in feeder J is shown in table 15.

Table XV. Number of Distribution Transformers in Feeder J

S. No.	Transformer Rating	Number of Transformers
1	16 kVA	0
2	25 kVA	42

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3	63 kVA	15
4	100 kVA	9

IV. Problem Analysis

The load flow analysis of the modeled system was performed using inbuilt load flow software module of ETAP software. The method used for load flow analysis is Newton-Raphson method with 0.0001 precision value and maximum iteration value of 99. The load flow analysis of the modeled system was performed at 50%, 60%, 70% and 80% loading category. The tapping of the 20 MVA power transformer was set at 4.375% during the load flow analysis.

1) Load Flow Results at 50% Loading Category: At 50% loading category, it was observed that all the buses were operating within their stable operating point. There were no unstable buses in the system. The load flow summary at 50% loading category is shown in table 16.

Table XVI. Load Flow Results at 50% Loading Category

S. N.	Study ID	Value
1.	Case Study	Load Flow
2.	Data Revision	Base
3.	Configuration	Normal
4.	Generation Category	Design
5.	Loading Category	50%
6.	Number of Buses	994
7.	Number of Branches	993
8.	Power Grids	1
9.	Load MW	9.742
10.	Load MVAR	5.746
11.	Loss MW	0.404
12.	Loss MVAR	0.852
13.	Generation MW	9.742
14.	Generation MVAR	5.746

2) Load Flow Results at 60% Loading Category: At 60% loading category, it was observed that there were 14 critically unstable buses and 161 marginally unstable buses present in the system. The load flow summary at 60 percent loading category is shown in the following table 17.

Table XVII. Load Flow Results at 60% Loading Category

S. N.	Study ID	Value
1.	Case Study	Load Flow
2.	Data Revision	Base
3.	Configuration	Normal
4.	Generation Category	Design
5.	Loading Category	50%
6.	Number of Buses	994
7.	Number of Branches	993
8.	Power Grids	1
9.	Load MW	11.729
10.	Load MVAR	7.128
11.	Loss MW	0.595
12.	Loss MVAR	1.293
13.	Generation MW	11.729
14.	Generation MVAR	7.128

The voltage profile of the system at 60% loading category is shown in Fig. 2.

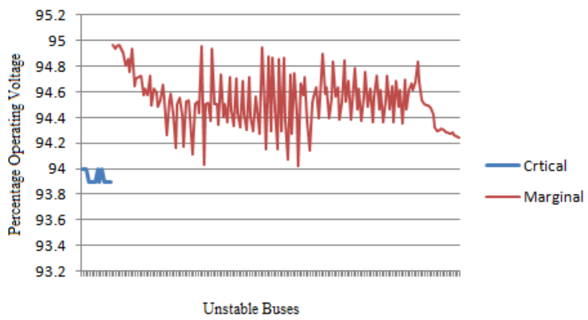

Fig. 2. Voltage Profile of the System at 60% Loading Category

3) Load Flow Results at 70% Loading Category: At 70% loading category, it was observed that there were 291 critically unstable buses and 148 marginally unstable buses present in the system. The load flow summary at 70 percent loading category is shown in the following table 18:

Table XVIII. Load Flow Results at 70% Loading Category

S. N.	Study ID	Value
1.	Case Study	Load Flow
2.	Data Revision	Base
3.	Configuration	Normal
4.	Generation Category	Design
5.	Loading Category	50%

6.	Number of Buses	994
7.	Number of Branches	993
8.	Power Grids	1
9.	Load MW	13.735
10.	Load MVAR	8.597
11.	Loss MW	0.83
12.	Loss MVAR	1.833
13.	Generation MW	13.735
14.	Generation MVAR	8.597

The voltage profile of the system at 70% loading category is shown in Fig. 3.

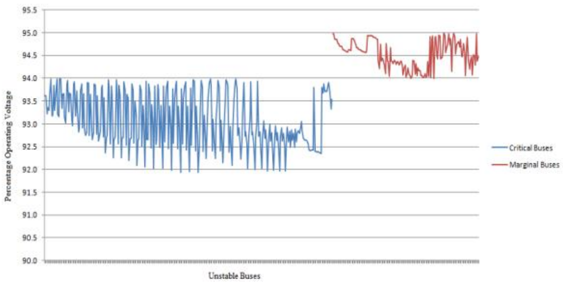

Fig. 3. Voltage Profile of the System at 70% Loading Category

4) Load Flow Results at 80% Loading Category: At 80% loading category, it was observed that there were 583 critically unstable buses and 140 marginally unstable buses present in the system. The load flow summary at 80 percent setting is shown in the following table 19:

Table XIX. Load Flow Results at 80% Loading Category

S. N.	Study ID	Value
1.	Case Study	Load Flow
2.	Data Revision	Base
3.	Configuration	Normal
4.	Generation Category	Design
5.	Loading Category	50%
6.	Number of Buses	994
7.	Number of Branches	993
8.	Power Grids	1
9.	Load MW	15.769
10.	Load MVAR	10.165
11.	Loss MW	1.112
12.	Loss MVAR	2.483
13.	Generation MW	15.769
14.	Generation MVAR	10.165

The voltage profile of the system is shown in the Fig. 4.

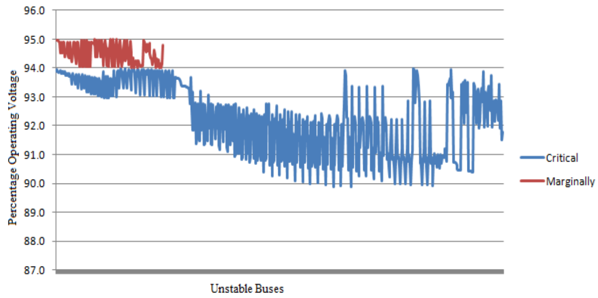

Fig. 4. Voltage Profile of the System at 80% Loading Category

The main cause of the poor voltage profile or voltage sag along the length of the power line was found to be the reactive power demand by the various system loads. This generally happens in case of the agricultural supply feeders because of presence of highly inductive load. Hence for improving the voltage profile of the system, it was suggested to install the capacitors for the reactive power compensation. In this assumed electrical network the reactive power compensation was to be given for the different loading categories i.e. for 60%, 70% and 80% loading category. It was analyzed from the load flow analysis of assumed electrical distribution system that the reactive power demand at 60% loading category is half as compared to that at 70 and 80 percent loading categories by the various system loads. The reactive power demand by loads at 70% and 80% loading category is shown in table 20.

Table XX. Reactive Power Demand by System Loads at 70 and 80 Percent Loading Category

S. N.	Transformer Rating	Rating of Switched Capacitor
1.	16 kVA	5 kVAR
2.	25 kVA	8 kVAR
3.	63 kVA	20 kVAR
4.	100 kVA	30*, 35 kVAR

* 30 kVAR is only required for feeder C and J.

From the above analysis, it was suggested that two switched capacitors each of half of rating as that the reactive power required at 80% loading category should be placed on the LV side of transformers starting from the first marginally unstable bus in each electrical feeder. This optimal placement of switched capacitors has improved the voltage profile of assumed electrical system and also has reduced the overall losses in the system. The load flow summary after the optimal capacitor placement (OCP) at 60%, 70% and 80% loading category is shown as follows:

1) Load Flow Results After OCP at 60% Loading Category: At 60 percent setting, the switched capacitors were placed for improving voltage profile and loss reduction of the assumed electrical system. The ratings of the switched capacitors are selected as half that is given in table 17 for respective transformer ratings. The summary of load flow report after placing switched capacitors at 60 percent setting is shown in the following table 21.

Table XXI. Load Flow Results after OCP at 60 Percent Loading Category

S. N.	Study ID	Value
1.	Case Study	Load Flow
2.	Data Revision	Base
3.	Configuration	Normal
4.	Generation Category	Design
5.	Loading Category	60%
6.	Number of Buses	994
7.	Number of Branches	993
8.	Power Grids	1
9.	Load MW	11.724
10.	Load MVAR	4.078
11.	Loss MW	0.485
12.	Loss MVAR	1.041
13.	Generation MW	11.724
14.	Generation MVAR	4.078

2) Load Flow Results after OCP at 70% Loading Category: At 70% loading category, the switched capacitors were placed on the LV side of the transformer with the ratings exactly as per table 17. The load flow summary at 70% loading category is shown in table 22.

Table XXII. Load Flow Results after OCP at 70 Percent Loading Category

S. N.	Study ID	Value
1.	Case Study	Load Flow
2.	Data Revision	Base
3.	Configuration	Normal
4.	Generation Category	Design
5.	Loading Category	50%
6.	Number of Buses	994
7.	Number of Branches	993
8.	Power Grids	1
9.	Load MW	13.77
10.	Load MVAR	2.507
11.	Loss MW	0.621
12.	Loss MVAR	1.349
13.	Generation MW	13.77
14.	Generation MVAR	2.507

3) Load Flow Results after OCP at 80% Loading Category: At 70% loading category, the switched capacitors were placed on the LV side of the transformer with the ratings exactly as per table 17. The load flow summary at 70% loading category is shown in table 23.

Table XXIII. Load Flow Results after OCP at 80 Percent Loading Category

S. N.	Study ID	Value
1.	Case Study	Load Flow
2.	Data Revision	Base
3.	Configuration	Normal
4.	Generation Category	Design
5.	Loading Category	50%
6.	Number of Buses	994
7.	Number of Branches	993
8.	Power Grids	1
9.	Load MW	15.768
10.	Load MVAR	4.159
11.	Loss MW	0.839
12.	Loss MVAR	1.858
13.	Generation MW	15.768
14.	Generation MVAR	4.159

V. RESULTS AND CONCLUSIONS

In this paper work, the voltage stability analysis of an assumed 20 MVA electrical radial distribution system was successfully performed using ETAP software. The critically and marginally weak buses or nodes were found using load flow analysis. The voltage profile of the system was improved using optimal switched capacitor placement. The switched capacitors were placed on the load side or low voltage side of distribution transformers, according to the reactive power demand by the load, starting from the first marginally unstable node or bus. As the unit size of the switched capacitors is selected according to the reactive power demand by the various loads at different loading categories, this scheme will constantly help in the improvement of voltage profile with the load variation. The comparison of the kilovolt ampere required by the power transformer before and after placement of the switched capacitors is shown in the table 24.

Table XXIV. Comparison of kVA Demand Before and After OCP

S. N.	OCP Placement	60% Loading (kVA)	70% Loading (kVA)	80% Loading (kVA)
1.	Before OCP	13177	15427	17707
2.	After OCP	12108	13758	15889
3.	Savings	1069	1669	1818

Hence, optimal capacitor placement on load side of distribution transformers not only improves the voltage profile of the system but also helps in savings of kilo volt amperes required.

It was also concluded that optimal switched capacitor placement on the load side also improves the power factor of every load in the system, hence improves the overall power factor of the complete system. In the assumed electrical network, the power factor of the complete system was improved from 88.1 percent to 98.4 percent. Hence, the optimal switched capacitor placement on the load side or low voltage side of distribution transformer helps in the voltage profile improvement along the length of power line and power loss reduction.

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