ANALYSIS OF APPLICATIONS OF LINE DROP COMPENSATION FOR LOW-COST SUBSTATIONS INSRI LANKA

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Abstract— **Voltage drop at distant locations of distribution lines create problems in many ways. Since most distribution transformers are equipped with Off-Circuit Tap Changers (OCTC), consumer voltage drops below the recommended limits. In Sri Lanka, this phenomenon has caused under voltages below 400 V at consumer side at long distances. So far, the solution has been to construct new substations at suchlocations. However, it is possible to use the "Line drop compensation" (LDC) option available in power transformer OLTC to mitigate this issue for some extent. In this study, we present up to which lengths line drop compensation option could be used to regulate line voltage at nominal level using a simulation model in DIgSILENT PowerFactory. Actual line, and equipment parameters were used in this study. Results show that load power factor has a direct correlation with the line length. Further, Automatic Voltage Regulator (AVR) and capacitor bank combination could be used to go for increased line distances. In conclusion, these options could be implemented in the Sri Lankan transmission network to increase the coverage of transmission grid substations. We can avoid costs on new transmission grid substations with this.**

Keywords - Line drop compensation; voltage drop; OLTC; DIgSILENT; substations.

I. INTRODUCTION

When a Medium Voltage (MV) short distribution line is considered, there is a voltage drop at distant locations due to the predominant nature of its resistance and inductance. Since most distribution transformers are equipped with Off- Circuit Tap Changers (OCTC), consumer side voltage dropsbelow the recommended limits. In Sri Lanka, this phenomenon in 33 kV MV distribution lines have caused under voltages below 400 V at consumer side at long distances. Till now, the solution has been to construct new substations at such locations.

However, modern AVRs of power transformer OLTCs come with a function "Line drop compensation" which enables increase coverage of the transmission lines by increasing the terminal voltage without exceeding its limits for highest voltage for equipment. In this study, we present up to which lengths line drop compensation option could be used to regulate line voltage at nominal level using a simulation model in DIgSILENT PowerFactory (PF). Actual line, and equipment parameters will be used in this study. Further, effects of adding capacitor banks at remote bus are also to be analyzed.

II. LITERATURE REVIEW

All voltage level control is a crucial step in ensuring the safe and effective functioning of an electric network. One hundred years ago, the energy distribution networks (EDN) were constructed, and for decades, they have been updated to address shifting end-user requirements. In conventional electrical networks, the central power plants generate the energy, which is then transmitted and distributed to the end user via EDN in a one-way fashion.

The Distribution Network Operators (DNOs) should keep the supplied voltage magnitude within mandated limits in order to maintain efficiency and reliability.

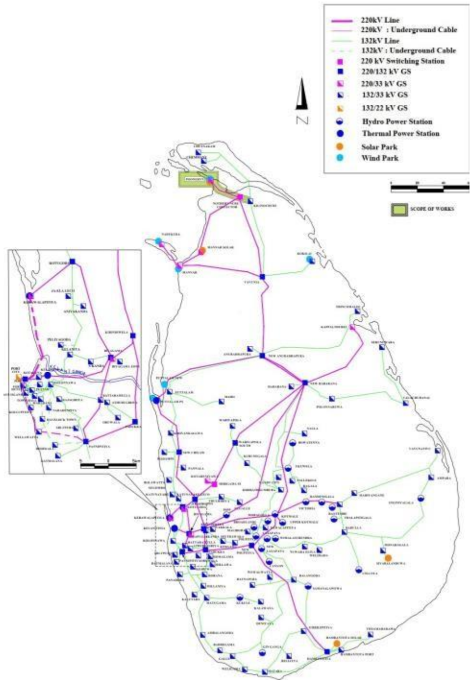


Figure 1. Transmission Network of Sri Lanka

Conventional EDNs were created with the idea that the HV/MV substation would be the only source of power, and when they are operated using conventional control methods, they can still show significant losses and poor voltage quality.

The OLTC of the electricity transformer in EDN substations is one example of a traditional voltage control asset that could be used to implement voltage regulation. Bus voltage optimization is a crucial job for DNOs as well because it increases loading capacity and maintains operational security.

As a result, the OLTC transformer with an automatic voltage control (AVC) relay, also known as AVR, is the most common voltage control mechanism [1-2]. The normalOLTC can alter the feeder voltage level of an EDN by about10%, according to [3]. There haven't been many researches done on the best voltage control techniques. For instance, in [4], the line drop compensation technique is used by the OLTC of the primary High Voltage (HV) or MV transformerto controlthe voltage magnitude.

In [5], an AVC relay uses the incoming current and the line impedance value to calculate the voltage drop along the power line between the supply source and the load. The writers of [6] suggest a technique for communicating with multiple voltage-regulating devices to coordinate voltage control. Additionally, [7] presents a method to identify OLTC tap changer variations while taking into considerationthe fact that end users can identify primary-side voltagemagnitude deviations at each load. A fuzzy logic-based control strategy for voltage stabilization by OLTC improvement is put forth in Paper [8].

An adaptive voltage control diagram is used in the article [9] to regulate the voltage of EDN. The problem-solving algorithm is the only thing that differs from the previously stated studies; the EDN structure and the overall structure of OLTC remain unchanged. By first determining the dispatch schedules of capacitors and then using an OLTC to regulate the voltage in real-time, the algorithms in [10] enable a two-stage voltage regulation diagram.

Other authors believe that in order to maintain the voltage constant at a fictitious regulation point in EDN, the distribution voltage must be controlled by an OLTC using the conventional line drop compensation (LDC) technique [11].

This paper investigates the usage of LDC technique in the context of the power distribution network of Sri Lanka. It further analyzed the usage of LDC with the combination of capacitor banks to increase the reach of the distribution network without constructing new costly substations or power distribution lines.

III. SYSTEM MODEL

A. Model Data

Typical 31.5 MVA and 45 MVA, 132/33 kV power transformers of CEB network were used for the study. 33 kV single circuit lines with single Zebra conductor and single Racoon conductor were used to observe the maximum possible line length. Racoon was selected since the majority of existing 33kV lines consists of single Racoon conductors.

Therefore, the study was carried out to examine the usage of the existing line as well. Existing maximum loads of the feeder 01 and 08 of Matara GS are around 9 MW and 3 MW. Feeder 01 supplies power to Weligama town. The power factor of the load varies between 0.9 to 0.99. Model was created to reflect similar scenario in which a local substation like Matara supplies power to remote bus such as Weligama.

TABLE I. 31.5 MVA TRANSFORMER RATINGS

Transformer Capacity	31.5 MVA
Impedance	10%
Load loss	120kW
No load loss	22kW
OLTC	1-11-18 (min-nom-max)*
Voltage of a tap	1.5%

TABLE II. 45 MVA TRANSFORMER RATINGS

TF MVA	45 MVA
Impedance	11%
Load loss	160kW
No load loss	27.5kW
OLTC	1-11-18 (min-nom-max)*
Voltage of a tap	1.5%

* PF interpretation of min and max tap are different than rating plate.

Setting up of the LDC in PowerFactory uses following data and steps. Derived Rset and Xset values will be used in the simulation. Distribution line reactance and resistances were calculated in the software based on the geometrical data.

CT ratio = 800/1 A = 800 (1)
VT ratio = (33000 / √3) / (110 / √3) V = 300 (2)
Rset = (800/300) x Resistance of the line (3)
Xset = (800/300) x Reactance of the line (4)

TABLE III. CONDUCTOR RATINGS

	Single Zebra	Single Racoon
DC resistance	0.0674 Ohm/km	0.3623 Ohm/km
Outer diameter	28.62 mm	12.3 mm
GMR	11.144 mm	4.789 mm

Twelve scenarios were analyzed. For the first ten scenarios, 31.5 MVA transformer was used. Considering the no load and load losses of the transformer and line, 28 MVA was the maximum load the 31.5 MVA transformer could cater to. For the last two scenarios, 45 MVA transformer was used with capacitor banks at remote bus to demonstrate the benefits of reactive power compensation at remote bus.

45 MVA transformer could cater to a maximum load of 43 MVA in those two scenarios. Capacitor banks were operating at voltage and reactive power control mode. With 45 MVA transformer, 18 Mvar of reactive power was required to operate close to power factor 1. Similarly, with 31.5 MVA transformer, 12 Mvar was required to achieve close to power factor 1.

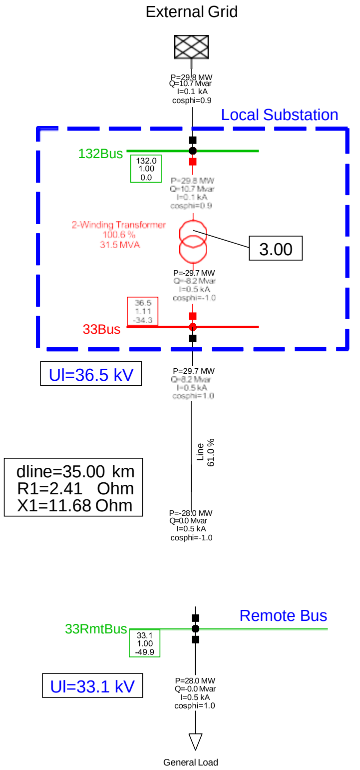


Figure 2. *Model of without capacitor bank*

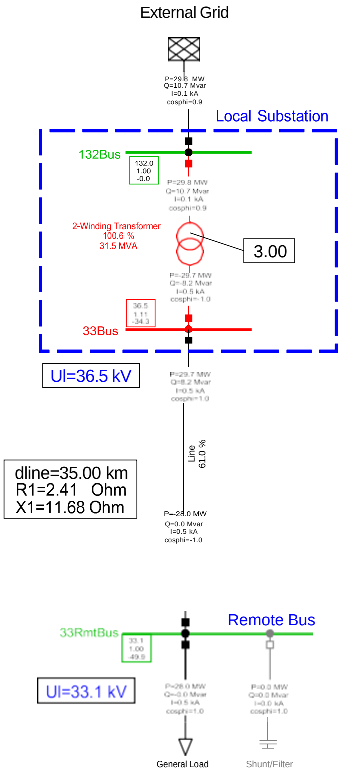
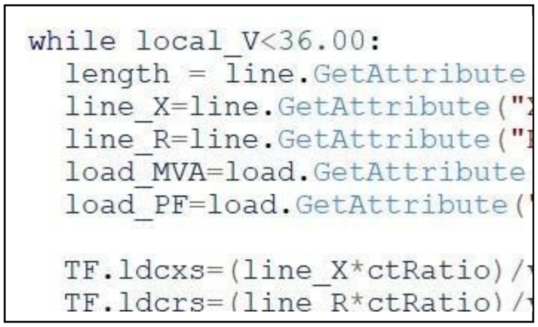


Figure 3. *Model of with capacitor bank*

B. *Program Script*

It is not practical to change the tap manually and record the maximum distance for each tap for all the twelve cases separately. Therefore, a program was used to get distance values with the varying taps for each case. The program was made using Python programming language to find the line distances with LDC. It calculated the distances up to which the sending end voltage could be kept below 36 kV while tapping range or operates. The values are given in an array which is then depicted in the graphs.



```
while local_V<36.00:
  length = line.GetAttribute
  line_X=line.GetAttribute("
  line_R=line.GetAttribute("
  load_MVA=load.GetAttribute
  load_PF=load.GetAttribute('

  TF.ldcxs=(line_X*ctRatio)/
  TF.ldcrs=(line_R*ctRatio)/
```

Figure 4. *Part of the Python Script*

IV. RESULTS AND DISCUSSION

LDC option predicts the remote end bus voltage based on the line resistance and reactance. AVR of the tf calculates the remote end voltage based on the line current, local busvoltage and the voltage drop along the line.

Based on above calculated values, tap position is adjusted so that the remote bus voltage remains within the tolerance. When the remote end calculated bus voltage reaches lower or upper boundaries of 1% from the 33 kV voltage, tapping increased or decreased accordingly.

In Fig. 5, with single zebra cable at 1.0 p.u. of 132 kV bus voltage, it is observed that the sending end voltage rises above 36 kV at 35 km line length. Therefore, the maximum length allowable is 34 km. The tapping range is not exceeded.It is at tap 15 at 34 km. It is simulated at different load powerfactors when other conditions such as 132 kV bus voltage and load kVA is kept constant. This showed thatthere is a positive relationship between line maximum lengthand load power factor when case No. 1 to 4 is compared.

Results of Cases 1, 2 and 3 illustrate same substation and line arrangement supplying same apparent power but with varying power factor. Power transfer distance is greatestwhen the load power factor is 1 and decreases when the loadpower factor is 0.95 and the lowest line distance is obtained when the power factor is 0.9. This is associated with higher reactive power flow at the lower power factors. Case 4compares the utilization of a higher rated transformer which results in a higher power flow. This creates a further voltagedrop and eventually ends up with a lower effectivedistribution line length.

Cases 5, 6, and 7 represent the cases 1, 2 and 3 with lower network voltage. In these cases, network voltage of 0.95 p.u. were applied to the substation 132 kV bus reflecting the typical low voltage behavior of the Southern part of the Sri Lankan network as shown in Fig 1.

TABLE I. SIMULATION RESULTS

No.	**Conductor**	**132 kV Bus voltage (p.u.)**	**Length (km)**	**Power Factor**	**Load**		
					MVA	***MW***	***Mvar***
1	Single Zebra	1	34	1	28	28	0
2	Single Zebra	1	17	0.95	28	26.6	8.7
3	Single Zebra	1	16	0.9	28	25.2	12.2
4	Single Zebra	1	10	0.9	43	38.7	18.7
5	Single Zebra	0.95	30	1	28	28	0
6	Single Zebra	0.95	18	0.95	28	26.6	8.7
7	Single Zebra	0.95	14	0.9	28	25.2	12.2
8	Single Racoon	1	15	1	16	16	0
9	Single Racoon	1	13	0.95	16	15.2	4.99
10	Single Racoon	1	11	0.9	16	14.4	6.97
11	Single Zebra + Cap (Q)	1	31	0.9	28	25.2	12.2
12	Single Zebra + Cap (V)	1	25	0.9	28	25.2	12.2
13	Single Zebra + Cap (Q)	1	23	0.9	43	38.7	18.7
14	Single Zebra + Cap (V)	1	15	0.9	43	38.7	18.7

From the results it is evident that lower network voltages help to slightly increase the effective power transfer lengths in each case above. When transformer capacity and load are increased, maximum line length decreases when case 3 and 4 are compared.

Simulations were also done for single racoon conductor, which is commonly used in the distribution network of Sri Lanka. It showed comparatively lower maximum line length when 132 kV bus voltage and load power factor was kept at 1 p.u. since the amperage is lower through racoon conductors.

A further step was taken to analyze the use of capacitor banks along with LDC in the distribution network. Capacitorbanks with multiple steps were considered for simulation purpose to measure the required reactive power compensation. The simulation was done with capacitor banks installed at remote bus when supplied through both 31.5 and 45 MVA transformers to observe the effectiveness of the capacitors on distribution line performance under two control methods as given in cases 11, 12, 13 and 14 respectively.

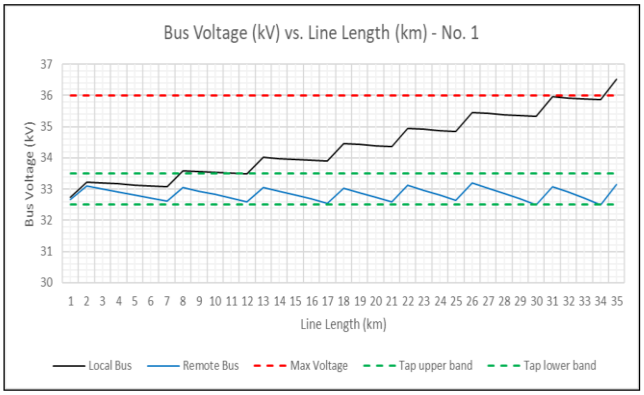


Figure 5. *Case 1 Bus Voltages*

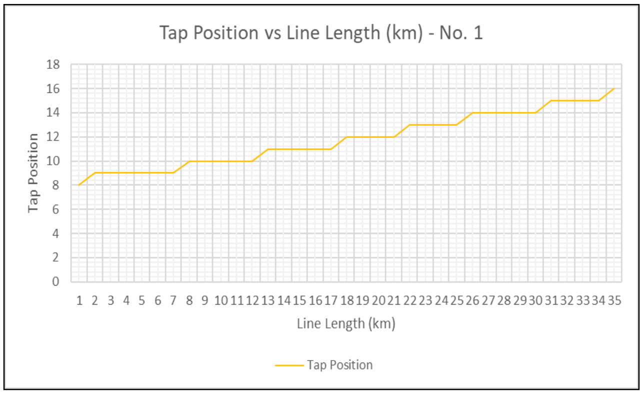


Figure 6. *Case 1 Tap Position*

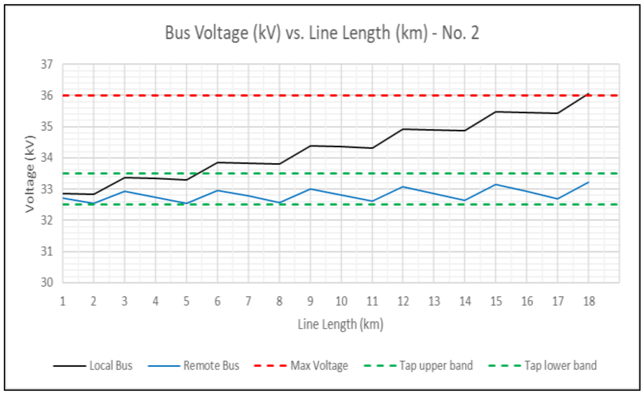


Figure 7. *Case 2 Bus Voltages*

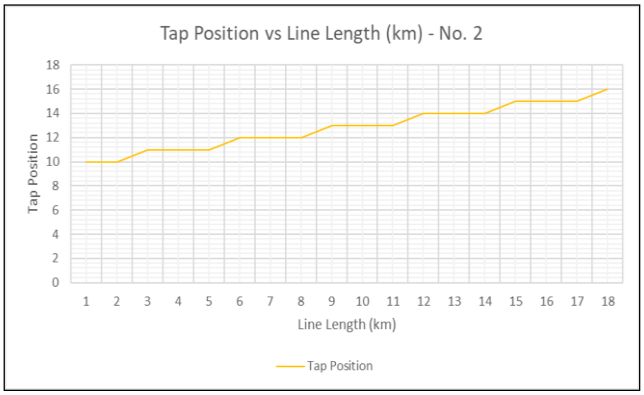


Figure 8. *Case 2 Tap Position*

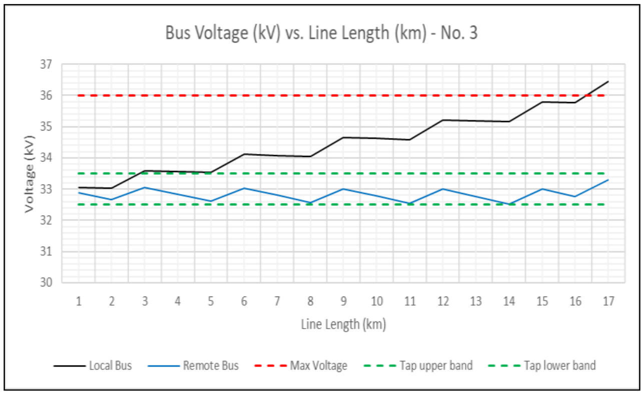


Figure 9. *Case 3 Bus Voltages*

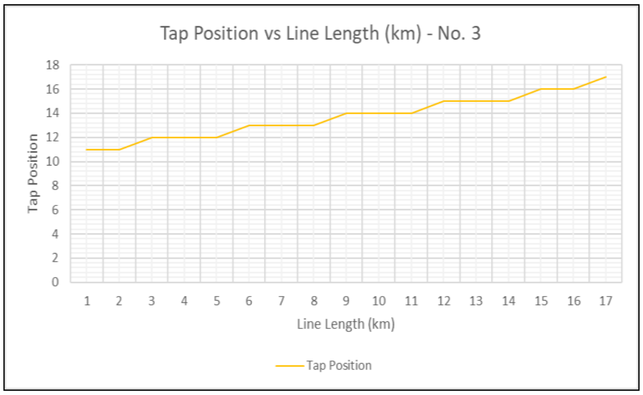


Figure 10 *Case 3 Tap Position*

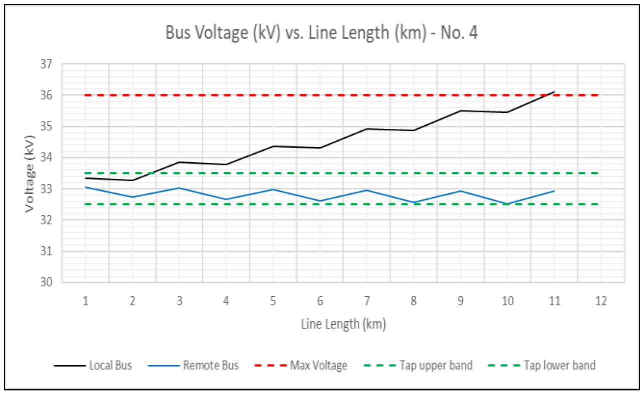


Figure 11. *Case 4 Bus Voltages*

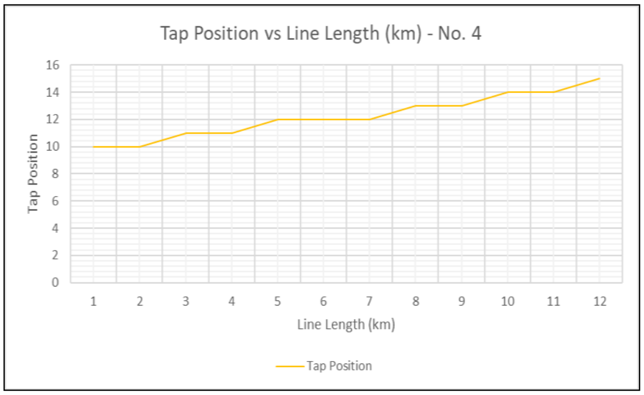


Figure 12. *Case 4 Bus Voltages*

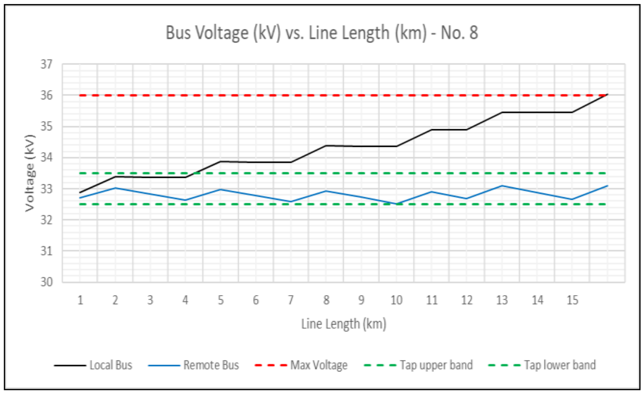


Figure 13. *Case 8 Bus Voltages*

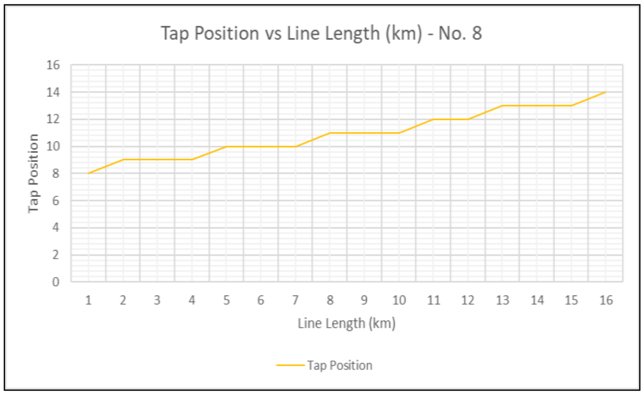


Figure 14. *Case 8 Tap Position*

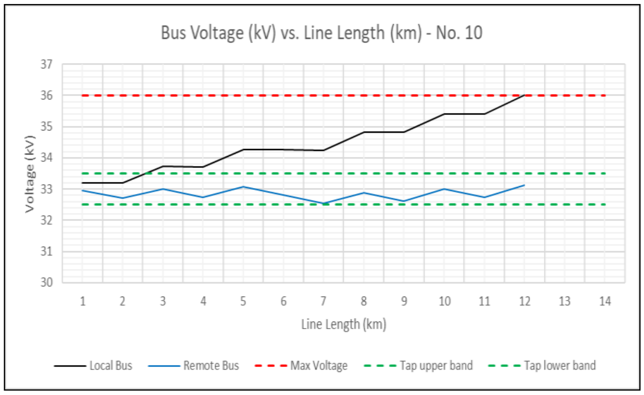


Figure 15. *Case 10 Bus Voltages*

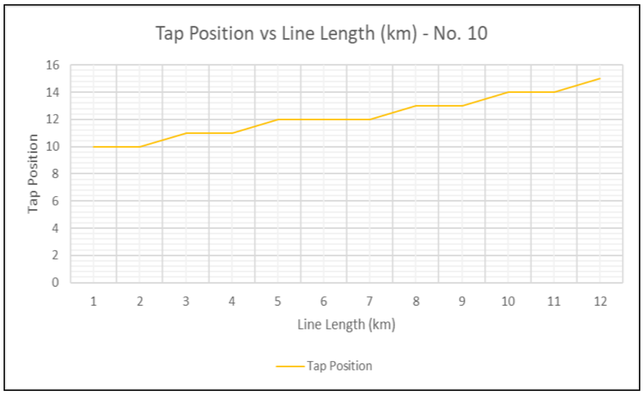


Figure 16. *Case 10 Tap Position*

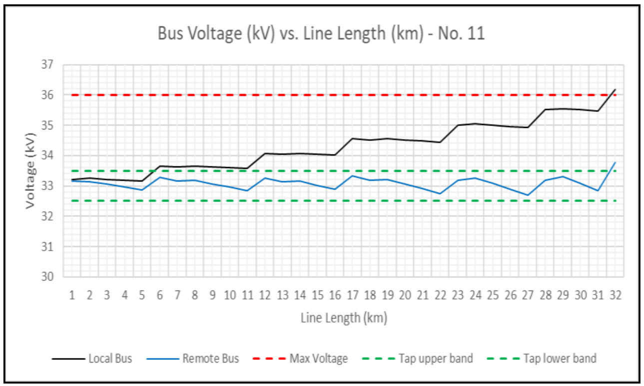


Figure 17. *Case 11 Bus Voltages*

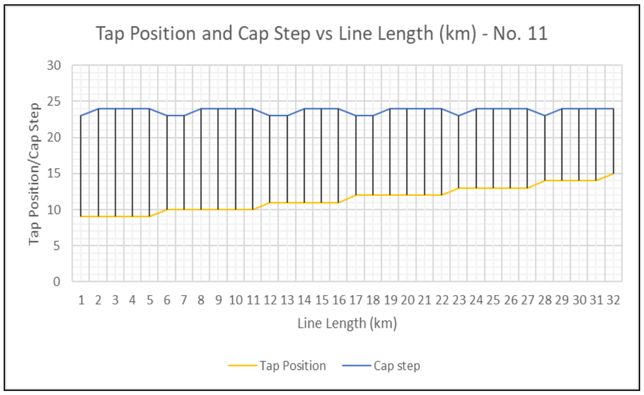


Figure 18. *Case 11 Tap Position and Cap Step*

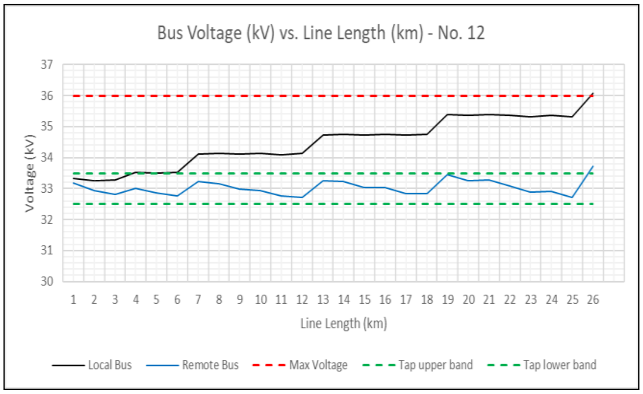


Figure 19. *Case 12 Bus Voltages*

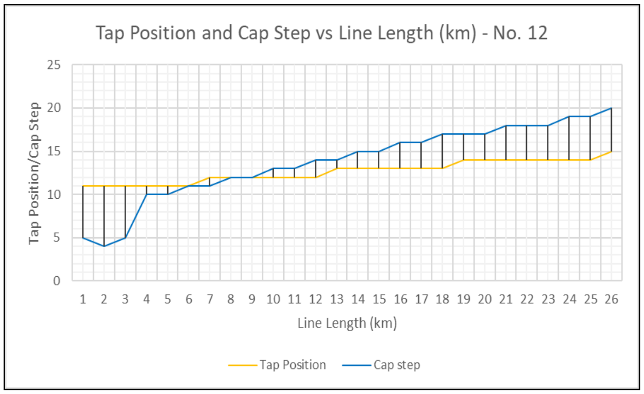


Figure 20. *Case 12 Tap Position and Cap Step*

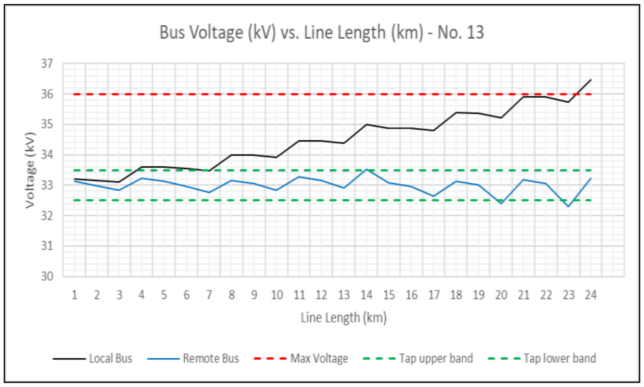


Figure 21. *Case 13 Bus Voltages*

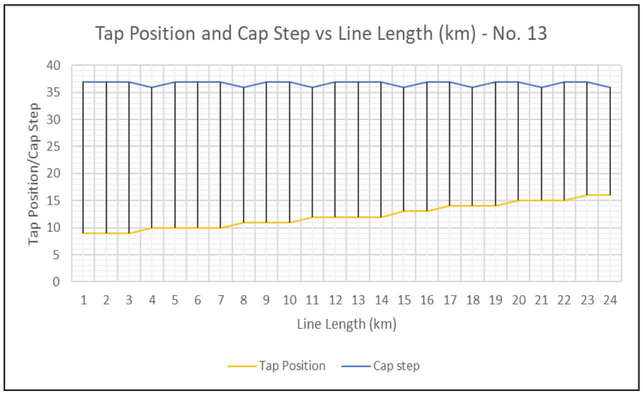


Figure 22. *Case 13 Tap Position and Cap Step*

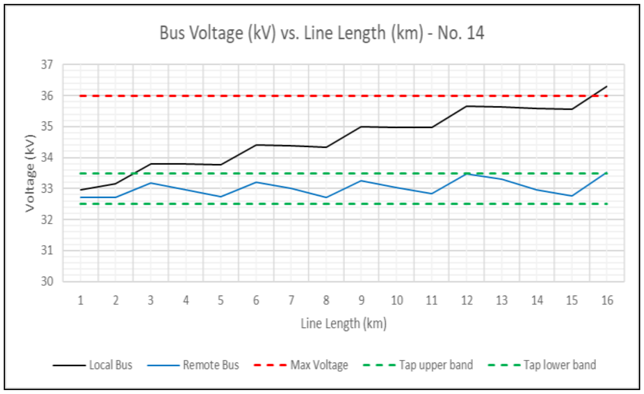


Figure 23. *Case 14 Bus Voltages*

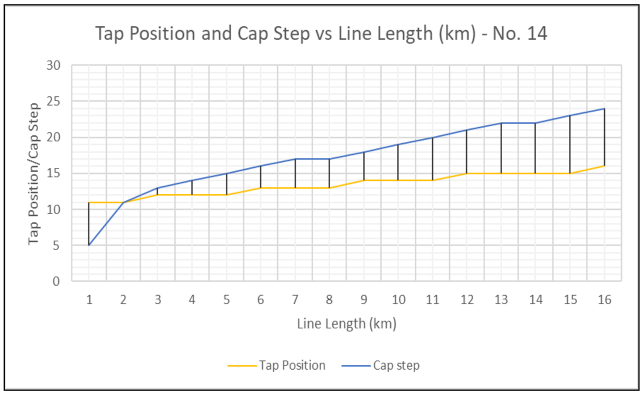


Figure 24. *Case 14 Tap Position and Cap Step*

When case 3 and 11 are compared, it is observed that the maximum line length could be doubled using a capacitor bank to cater to the reactive power requirement of the load. In reactive power control mode (Q control), capacitor bank acts to minimize the reactive power flow through the distribution line towards the load, effectively compensating reactive power requirement. In the voltage control mode (V control), capacitor bank is used to control the voltage of the remote bus. In both cases, capacitor banks are installed at 33 kV remote bus.

In V control mode, AVR and capacitor controllers should have different response times to avoid any hunting event occurring between them. In a scenario where AVR has less response time than the capacitor controller, AVR tends to increase or decrease the tap position of the transformer to regulate the voltage before the capacitor bank acts to inject the reactive power. Capacitor controller must be set to act faster to give a fast response while AVR acts as the backup option. Cases 3 and 4 were compared with both capacitor control modes (Q control and V control) in cases 11, 12, 13 and 14 respectively.

Q control mode shows promising results by effectively increasing the power transfer distances in cases 11 and 13 when compared with cases 3 and 4. This is a result of lower reactive power flow (Q flow) through the distribution line after compensating reactive power. On the other hand, V control mode is not as effective as Q control mode, but still shows greater distances than cases 3 and 4.

In addition, V control mode ensures that the remote bus voltage is always kept within the tolerance of ± 1% of the rated voltage, whereas Q control mode can cause slight violations beyond the tolerance to the remote bus voltage band. When cases 11 to 14 are compared, it is evident that in the V control mode, the capacitor bank switches gradually to keep up with the voltage changes of the remote bus. But, in the Q control mode, since the load reactive power requirement is fixed, the capacitor bank is also operating at almost a fixed step to compensate the reactive power requirement from the beginning, rather than changing steps with voltage variation.

V. RECOMMENDATIONS

LDC option of the AVR can be effectively used to increase the power transfer distances and improve the quality of the supply voltages in remote areas of Sri Lanka. Generally, in grid substations, two power transformers are used in parallel operation to maintain N-1 criteria as a reliability concern. However, LDC option can only be used with a dedicated transformer which is installed at the local substation. The other substation transformers which control the local substation 33 kV bus voltage cannot be paralleled with an LDC enabled transformer as these two types control two different buses.

Thus, a dedicated transformer with dedicated 33 kV feeder should be used at the substation to obtain the desired results. This combination is the most cost-effective solution as it avoids construction of completely new substations at the remote load center.

On the other hand, capacitor banks could be used to cater to the reactive power requirements of the loads and further enhance the maximum reach of the 33 kV distribution lines. Deployment of a capacitor bank is comparatively a complex task as it requires costly 33 kV switchgear such as breakers installed at the remote bus to switch the capacitors. In addition, separate control and relay panels with a control room must be installed to accommodate capacitor controllers and protection relays.

Furthermore, capacitors are most cost effective whenused with specific step sizes. Large step sizes (i.e. lower number of steps) can cause voltage violation and risky capacitor switching scenarios such as high inrush currents and circuit breaker re-striking. Small step sizes (i.e. higher number of steps) on the other hand can be extremely expensive. Therefore, an ideal size shall be worked out in a separate study in a simulation software such as DIgSILENT,and the control philosophy must be further examined.

Additionally, it is recommended that the LDC option should be incorporated in the grid specification of the transmission network and technical guaranteed particulars of each tender to make sure of the availability of this option which could save billions to the country’s economy.

Capacitor banks can be used effectively to inject the reactive power requirement of loads to increase the bus voltage levels. This will reduce the number of operations of the OLTC, which in return reduces the maintenance requirements of OLTCs. This significantly increases the lifetime of OLTCs.

VI. CONCLUSION

In this study, we have simulated the use of LDC option in AVRs to increase the power transfer distance of distribution lines. We used a model created in DIgSILENT power system simulation software for the simulation of 14 different scenarios. Further, analysis was done using capacitor banks in the remote buses to compensate reactive power requirements of the loads. Study cases include various load power factors, different transformer sizes, differentconductor types, and several network voltages.

Results show that with LDC option, we can transferpower to greater distances through distribution voltages without exceeding the permitted tolerance limits. This enables us to utilize the existing distribution network to enhance the maximum reach rather than construction new transmission lines and substations which are extremely expensive and time consuming.

Along with this study, capacitor bank usage was also simulated. Results showed that usage of capacitor bankscould further improve the maximum power transfer distances, while almost doubling the effective distances. Further, Q control mode of capacitor banks showed the mostpromising results compared to V control mode, regarding the power transfer distance of the distribution lines and lifetime of OLTCs of the transformers. Lifetime of the OLTCs couldbe significantly improved with reduced number of yearly operations as Q control mode acts to compensate the reactive power requirements of the load from the beginning, rather than letting the AVR change the tap position to maintain the voltage of the remote bus.

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