Reactive Power Compensation System for LV Distribution Network

Major Project Report

Submitted in Partial Fulfillment of the Requirements for the Degree of

MASTER OF TECHNOLOGY

IN

ELECTRICAL ENGINEERING

(Electrical Power Systems)

By

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CERTIFICATE

This is to certify that the Major Project Report entitled **"Reactive Power Compensation System for LV Distribution Network"** submitted by **Mr. Suketu Rajyaguru (15MEEE19)** towards the partial fulfillment of the requirements for the award of degree in Master of Technology (Electrical Engineering) in the field of Electrical Power Systems of Nirma University is the record of work carried out by him under our supervision and guidance. The work submitted has in our opinion reached a level required for being accepted for examination. The results embodied in this major project work to the best of our knowledge have not been submitted to any other University or Institution for award of any degree or diploma.
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I would like to express my immense gratitude to Prof. S. S. Kanojia (Assistant Professor, Department of Electrical Engineering, Institute of Technology, Nirma University, Ahmedabad) for her valuable guidance, motivation and encouragement throughout my preface of project. Her constant support and interest equipped me with a great understanding of different aspects. Her supervision and direction right from beginning motivate me to complete this period of project.

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Abstarct

The decentralised reactive power compensation is used now a days in the LV distribution system by using the capacitor banks. But there are certain issues for using this capacitor banks as decentralised manner. Those issues can be overcome by using the centralised reactive power compensation method. By centralizing capacitor banks together, it can help to maintain bus voltages and power factors as well as reduce the power cable losses. Also the centralized reactive power system can be easily expanded to meet any future load increase which can not be done by using the decentralised compensation system. A reasonably sized centralized reactive power compensation system will be capable of meeting the requirements of the network with optimal solutions. So here optimization will also be done for centralised reactive power compensation system. Here the bus voltage will also be maintained and power losses will be reduced by using the centralised reactive power compensation with capacitor bank. The simulation of the centralized reactive power compensation used distribution network will be done with appropriate software.

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Chapter 1

Introduction

1.1 Need of Reactive Power

Active power is necessary for running of any type of the electrical load. To transmit this active power from generation to the electrical loads, Reactive power is necessary. Generally the reactive power regulates the voltage level of power system. If voltage of the system is not sufficient, essential active power cannot be supplied. So reactive power is used to maintain the enough voltage for active power to do useful work.

1.2 Need of Reactive Power Compensation

Now a days power systems are being more reliable so that they can meet customers load demand without any interruption and with sufficient voltage. Generation facilities produces the required amount of power to meet the customers load demand. This power must be reached to the customer end through transmission and distribution systems.
Sometimes voltage may get to lower value and current increases to high value, causes power losses in a distribution system. Total power loss is the sum of both active and reactive power losses. To reduce this reactive power losses, Reactive Power Compensation is needed.
Compensation reduces the transmitted apparent power or total power. (See Fig.1.1). And ohmic transmission losses decrease by the square of the currents.

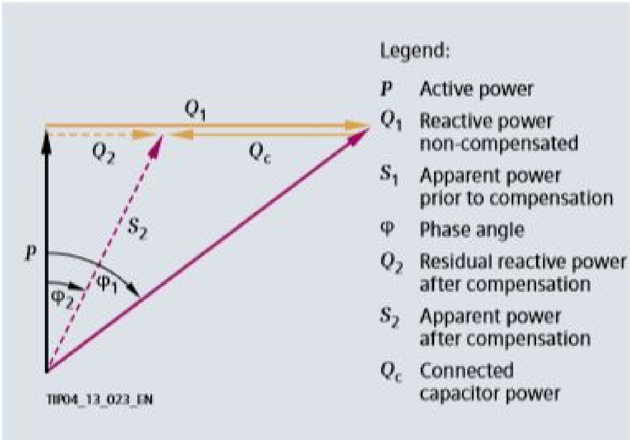


Figure 1.1: Power diagram for non-compensated and compensated installation

So, reactive power compensation strategies in power distribution systems is needed to reducing resistive power losses, control system voltage levels and improve power factors.

1.3 Device used for Reactive Power Compensation

Different devices can be used for reactive power compensation i.e. Static VAR Compensation (SVC), Capacitor Bank, FACT devices.
The static var compensator (SVC) and FACT devices depend on power electronics control techniques for reactive power compensation. The cost of these power electronics devices is very high. The other option for compensation is Capacitor Bank which is cost benefit as compare to SVCs and FACTs.
So for the LV distribution, capacitor bank is more preferable.

1.3.1 Capacitor Bank

As above discussion, the capacitor bank is better choice for reactive power compensation in distribution network. Static capacitor can further be subdivided in to two types such as Shunt capacitors and Series capacitor.

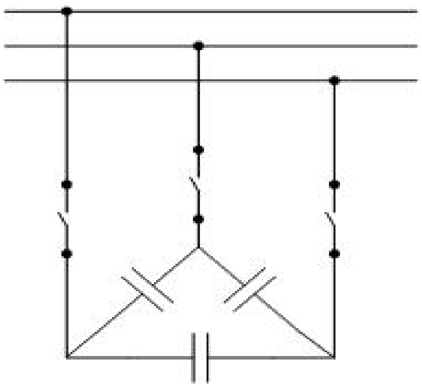


Figure 1.2: Capacitor Bank

The shunt capacitor is more commonly used among these two types. Some specific advantages are as below,

- Reduction in line current
- Improves voltage
- Improves power factor of the source current
- Reduction in system losses
- Reduces load of generators

1.4 Method used for Reactive Power Compensation

1.4.1 Decentralized Method

In decentralized reactive power compensation, the individual capacitor bank is installed locally in the network. The optimal size of capacitor bank can be obtained and install it wherever it is required for different period of times.

In this compensation method, capacitor can be used as single or group compensation.

- Single Compensation
  The capacitors are directly connected to the individual power load in the single compensation. This is possible when large reactive power demands for long time periods.

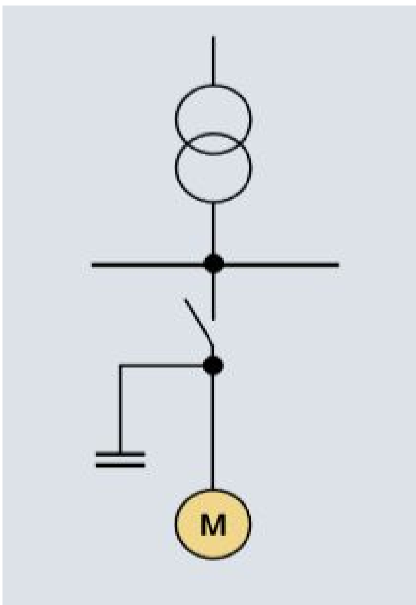


Figure 1.3: Single Compensation

- Grouped Compensation
  Each compensation device is assigned to a load group in group compensation. This group may be the concurrent type of the load (i.e. motors, lamps with electronic ballast).

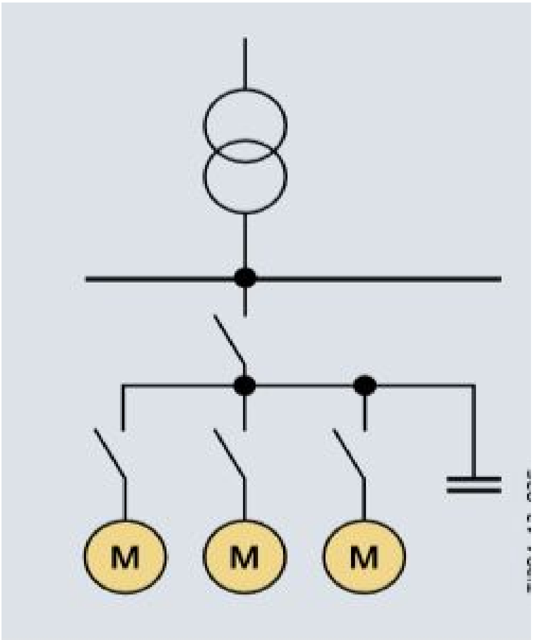


Figure 1.4: Group Compensation

1.4.2 Centralized Method

The control of the reactive power for every load is done centrally in centralized compensation method. Control units contain switchable capacitor branch circuits and a controller which acquires the reactive power present at the feed-in location. If it deviates from the set-point, the controller switches the capacitors on or off.

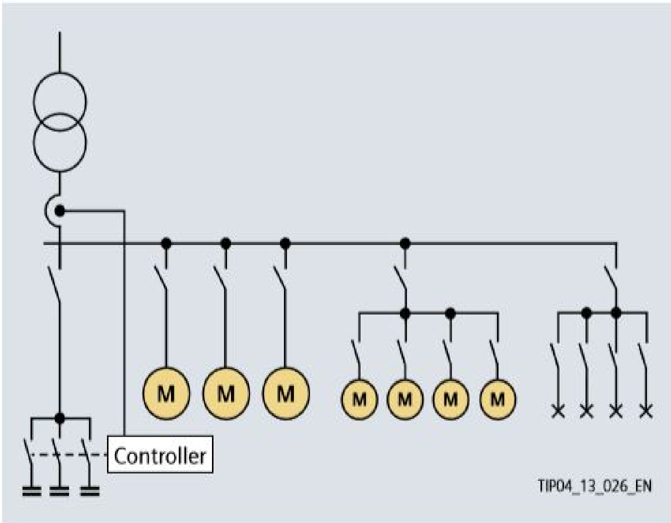


Figure 1.5: Central Compensation

1.5 Problem Identification

The current industry practice uses the decentralized method for reactive power compensation. In decentralized reactive power compensation, the individual capacitor bank is installed locally in the network. It is very costly and uneconomical to buy a capacitor bank and install it wherever it is required for different period of times. For that optimal size of capacitor bank can be obtained.

Also the decentralized method provide optimal capacitor placement for only one particular load situation. If the load situation changes, the new set of optimal capacitor placement will be given by the decentralized method. Also it is not possible practically to move capacitor bank from one location to other.

Another problem is the capacity of the capacitor bank is fixed to the maximum level. So capacitor banks at some buses with low load are unable to share their excess capacity of reactive power with other buses that have heavy load.

So these are certain issues or problems of decentralized reactive power compensation method.

1.6 Objective

The solution of the above said problem can be done by changing the method of reactive power compensation. By using the Centralized Reactive Power Compensation method instead of conventional method will give certain advantages over said problem.

In centralized reactive power compensation method, all the individual capacitor banks installed in the network are centralized. This will use for maintaining bus voltages and power factors. By centralizing all capacitor banks, the total capacity can be shared by each connected bus. It can also help to reduce the total installed capacity of capacitor banks instead of installing individual capacitor banks locally. Besides, the centralized reactive system can be easily expanded to meet any future load increase.

The other advantage of this system is reduction in the power cable loss because of less amount of cable is required.

This method takes into account the different load situations to classify the bus load groups into different load scenarios. The proposed centralized capacitor bank can also connect to as many buses as they require so there is no need to move the centralized capacitor bank around.

Chapter 2

Literature Survey

Literature survey consists of different research papers which gives fundamental knowledge about different electrical aspects related to project work.

(1) S. X. Chen, Y. S. Foo. Eddy, H. B. Gooi, M. Q. Wang, S. F. Lu, "A Centralized Reactive Power Compensation System for LV Distribution Networks," IEEE Transaction Power System, Vol.30, NO.1, January-2015.

- This paper is basically proposed a centralized method for reactive power compensation for the low voltage distribution system. The centralized capacitor bank is connected to some set of buses. By centralizing capacitor banks together, it can help to maintain bus voltages and power factors as well as reduce the power cable losses. Also this method is useful for the future load demand.
- One algorithm is proposed in this paper by which the optimal size of the centralized capacitor bank can be done by minimizing the expected total cost. The concept of the centralized reactive power compensation system is applied to a 59-bus local shipyard power system of Singapore to verify its effectiveness in this paper.
- The results show that centralized capacitor bank is capable to maintain bus voltages with reduced power losses.

(2) H. Shateri, M. Ghorbani, A. H. Mohammad-Khani, B.Ahmad-Khan-Beigi, "Load Flow Method for Distribution Networks with Automatic Power Factor Controller," UPEC 2011, 46th International Universities' Power Engineering Conference, 5-8th September 2011.

- This paper introduce a new methodology for load flow solution of distribution system. The conventional methods of load flow are not be used because the probability of convergence will be low. Also the power factor correction can be done in

said method.
- Firstly, the numbering can be done of every node of the distribution system (initialization from source). Then backward and forward sweeping can be done for the system load flow solution. Backward sweeping gives the current values at the different nodes while forward sweeping gives the voltage values at different nodes. Also the status of automatic power factor controllers capacitor banks switches can be checked. The power losses calculation also can be done here.
- So this paper gives a method for solution of load flow in distribution network.

(3) Pravin Chopade, Dr. Marwan Bikdash, "Minimizing Cost and Power loss by Optimal Placement of Capacitor using ETAP," IEEE 2011.

- This paper gives the optimal sizing and placement of the capacitor bank on the interconnected distribution system. The genetic algorithm method is used for the said optimization in ETAP software. The power losses, voltage regulation and cost of the capacitor are compared with radial, loop and interconnected distribution system.
- Harmonic component should affect the cost optimization. By considering only linear loads, the loop and interconnected system offers lower losses and provide better annual benefits, while redial system offers best annual benefits by capacitor placement. And in distorted networks, interconnected system provides the lower loss, cost benefits by capacitor placement.

(4) S. X. Chen, H. B. Gooi, "Capacitor Planning of Power Systems with Wind Generators and PV Arrays," IEEE-2009.

- This paper presents the economical optimization of the capacitor planning in the system. One IEEE system is tested with fossil fuel, wind generator and PV arrays together in paper.
- The objective is not only the minimization of cost of capacitor but also to minimize the cost of power loss. The cost function of the capacitor includes the one-time cost, maintenance cost, capacitors life time and interest rate for financing the installed capacitors. The optimization of the capacitor cost and the cost of power losses is done.

(5) Yongjun Zhang, Chao Chen, Minchuan Liao, "Study on Lv and Mv Integrated Reactive Power Optimization in Distribution Networks," Technical Session-1, Distribution network equipment, CICED-2008.

- This paper presented the reactive power optimization technique for the MV and LV distribution system. This paper proposed an optimization model of 10/0.4kV integrated reactive power compensation.
- Here two types of compensation i.e. Grouping compensation and Fixed compensation had been used at the MV side 10kV side. Other two types of compensation i.e. Phase splitting and Unified compensation had been used on the LV side of transformer 0.4kV side.
- Various parameters like power factor correction, power loss cost, voltage regulation improved by adjusting various types of MV and LV compensation.

(6) Jong-Young Park, Jin-Man Sohn, Jong-Keun Park, "Optimal Capacitor Allocation in a Distribution System Considering Operation Costs," IEEE Transactions on Power Systems, Vol. 24, No-1, February-2009.

- This paper proposed the planning method for capacitor installation in a distribution system to reduce the annualized installation costs and minimize the loss of electrical energy. The annualized installation cost related with the lifetime of device and number of operations of that device. The optimal solution for costs was determined using a genetic algorithm method.
- The 69 bus distribution system was proposed in this paper. The result was compared to that of the conventional method in which the lifetime of devices is not considered.
- The results show that the annualized costs is lower with the capacitor allocation determined by the proposed method. However the energy loss cost is slightly higher in this proposed method.

Chapter 3

Case Study

3.1 IEEE 13 Bus Test Feeder

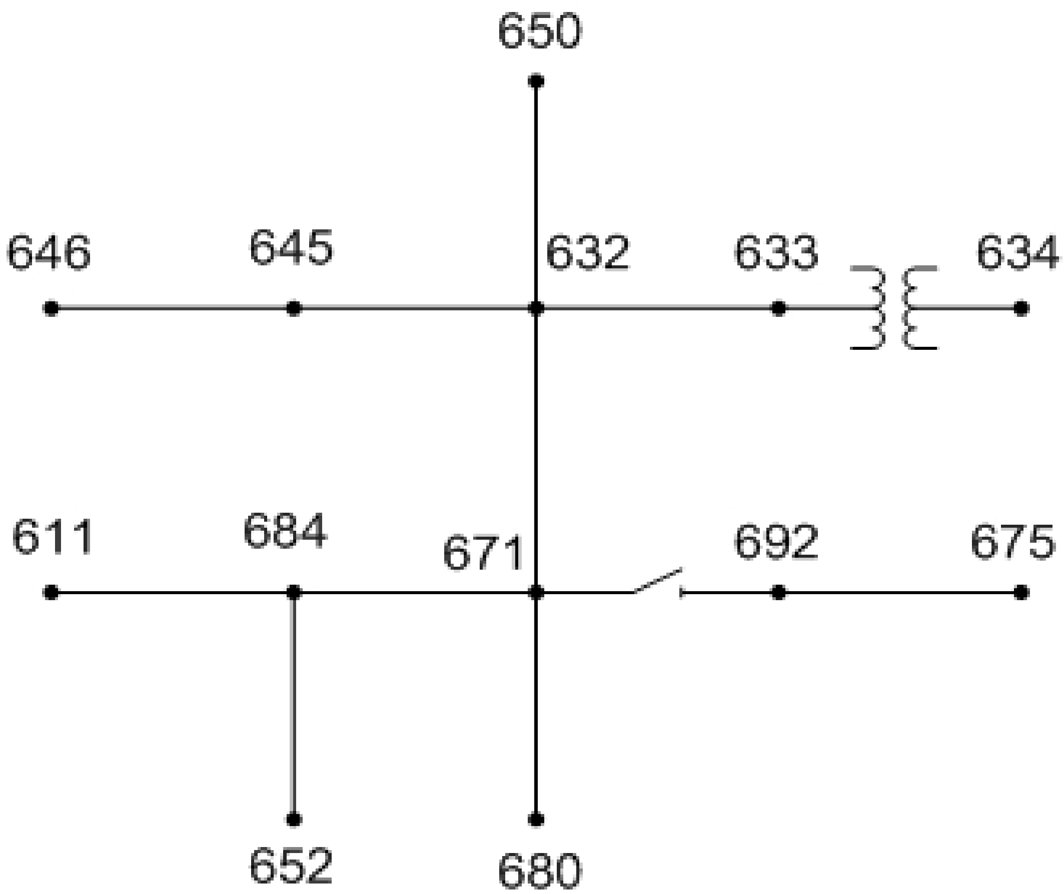


Figure 3.1: Single Line Diagram

The single line diagram of the IEEE 13 bus test feeder is shown in Fig-3.1. This system is taken as 13 bus distribution system for this case study for different comparisons.

3.2 Matlab Simulation

Here the simulation for 13 bus distribution system is done on the Matlab software. The voltage level for this system is 4.16kV. One 4.16/0.48kV three-phase transformer is connected. All the data for different components of the distribution system is taken from the standard IEEE test feeder for reference.

The simulation for the different cases are done as below.

3.2.1 13 Bus Distribution System without Capacitor

- Simulation of the 13 bus distribution system is done without any external capacitor.

3.2.2 13 Bus Distribution System with Decentralized Capacitor

- For decentralized capacitor, 3 three-phase delta connected capacitors of 200kvar(in each phase) are connected to the buses 671, 692, 675 and 2 single-phase capacitor of 200kvar are connected to the buses 684, 611.

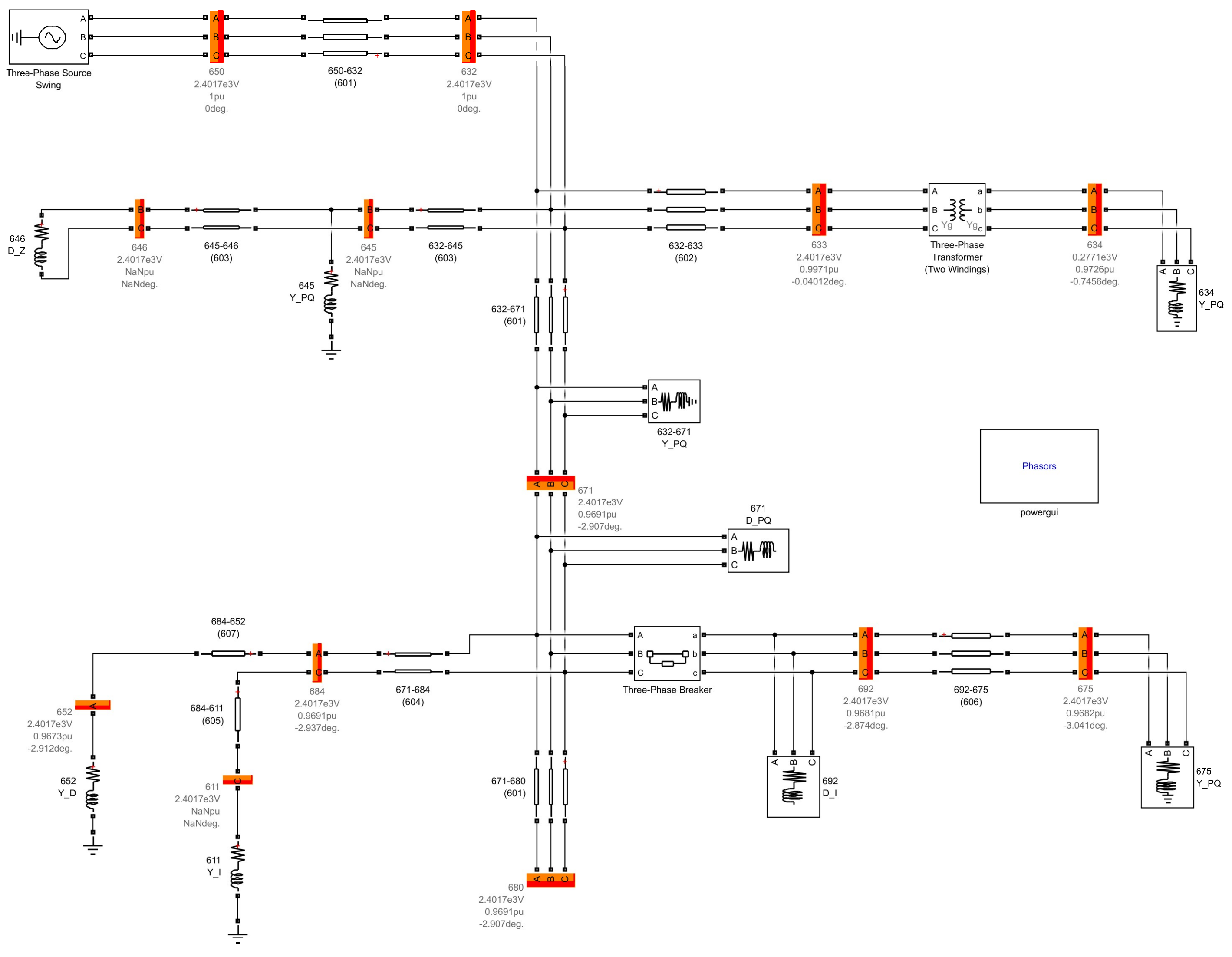
3.2.3 13 Bus Distribution System with Centralized Capacitor at Bus-632 (Case-1)

- For the centralized capacitor, one three-phase capacitor of 700kvar capacity in each phase is connected to bus 632 in case-1.

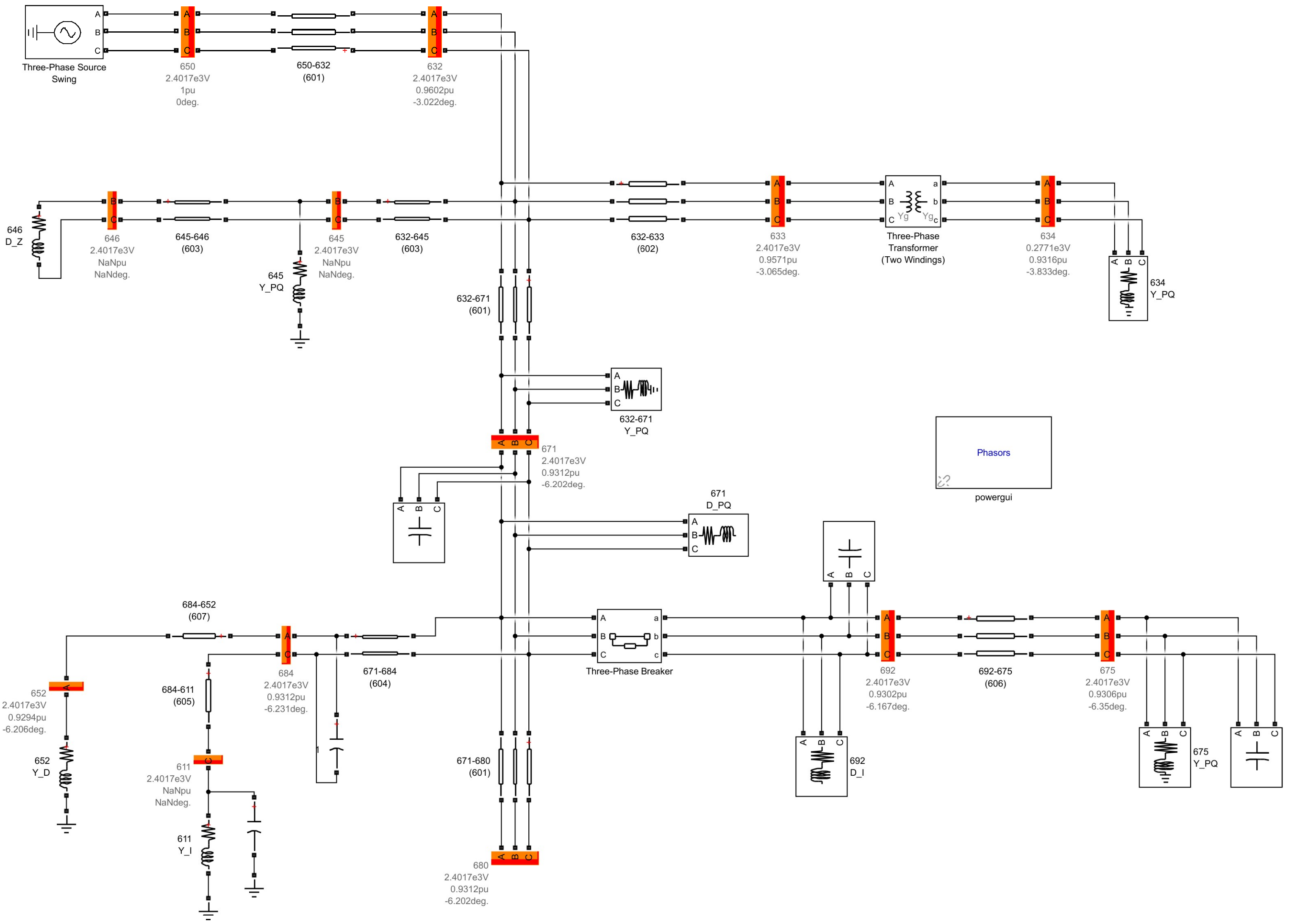
3.2.4 13 Bus Distribution System with Centralized Capacitor at Bus-680 (Case-2)

- For the centralized capacitor, one three-phase capacitor of 600kvar capacity in each phase is connected to bus 680 in case-2.

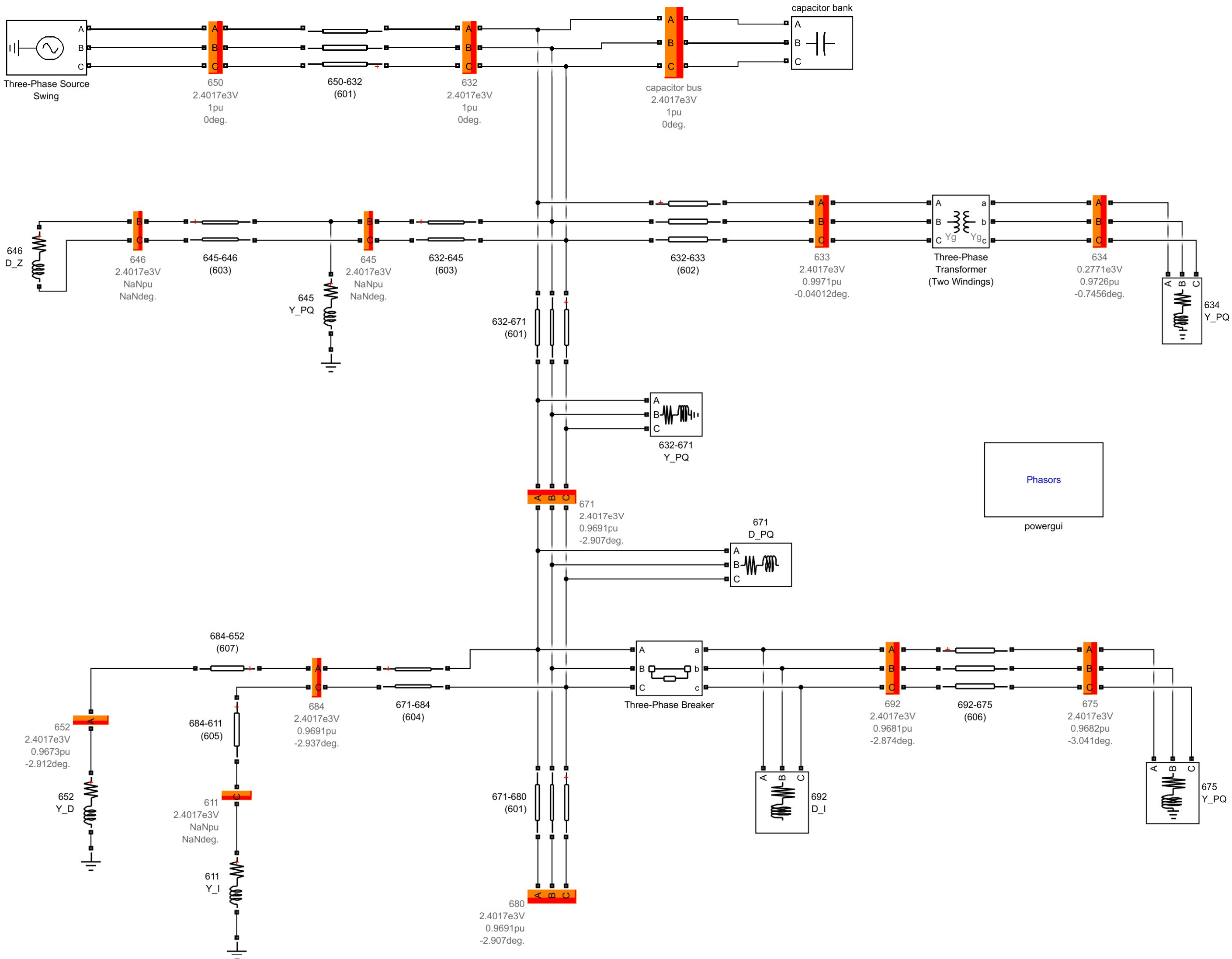
13 BUS DISTRIBUTION SYSTEM WITHOUT CAPACITOR



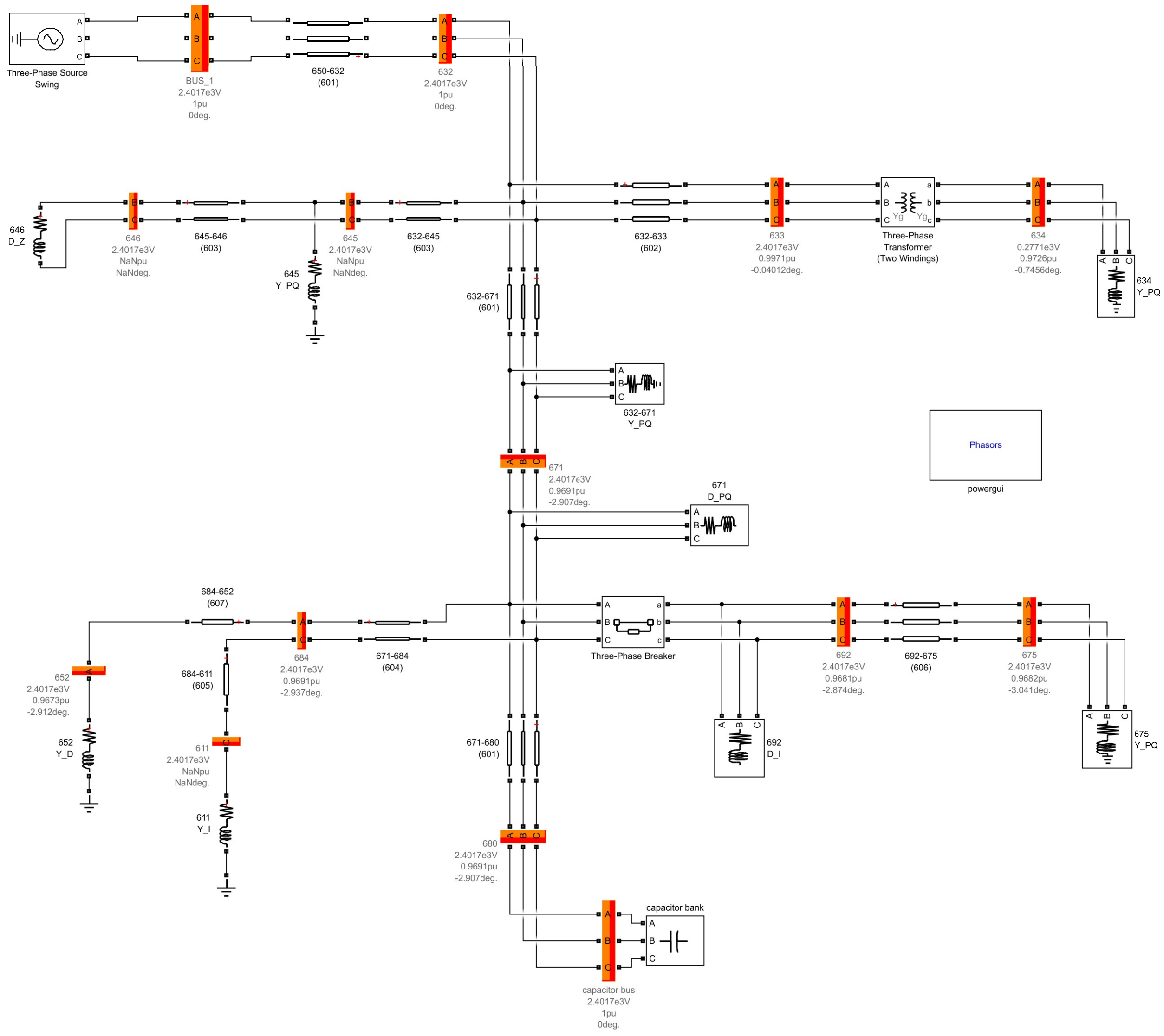
13 BUS DISTRIBUTION SYSTEM WITH DECENTRALIZED CAPACITOR



13 BUS DISTRIBUTION SYSTEM WITH CENTRALIZED CAPACITOR (BUS-632)



13 BUS DISTRIBUTION SYSTEM WITH CENTRALIZED CAPACITOR (BUS-680)



3.3 Results

The load flow simulations of 13 bus distribution system without capacitor, with decentralized and with centralized capacitor(case 1 & 2) are done on Matlab software. Voltage at different buses and the power loss for above cases are obtained after the load flow simulation. The comparison and analysis of these parameters for different cases is discussed in this section.

3.3.1 Voltages at different Buses

The voltage at each buses for 13 bus distribution system without capacitor, with decentralized and with centralized capacitor(case 1 & 2) after load flow simulation are shown in the Table 3.1.

Table 3.1: Voltage at different buses

BUS ID	**VOLTAGE (pu)**			
	Without Capacitor	**Decentralized Capcitor**	**Centralized Capacitor**	
			At Bus-632	**At Bus-680**
650_a	1	1	1	1
650_b	1	1	1	1
650_c	1	1	1	1
632_a	0.9602	0.9889	0.99	0.9857
632_b	0.9644	0.9858	0.9916	0.9876
632_c	0.9395	0.9717	0.9657	0.9625
633_a	0.9571	0.9859	0.987	0.9827
633_b	0.9624	0.9839	0.9896	0.9857
633_c	0.9368	0.9691	0.963	0.9599
634_a	0.9316	0.9611	0.9623	0.9579
634_b	0.9426	0.9645	0.9704	0.9663
634_c	0.9163	0.9494	0.9432	0.94
645_b	0.9549	0.9765	0.9823	0.9783
645_c	0.9378	0.97	0.9639	0.9608
646_b	0.9533	0.9748	0.9806	0.9766
646_c	0.9359	0.968	0.962	0.9588
671_a	0.9312	0.9886	0.9617	0.9822
671_b	0.9486	0.9915	0.9762	0.995
671_c	0.8836	0.9485	0.9111	0.9302
680_a	0.9312	0.9886	0.9617	0.9945
680_b	0.9486	0.9915	0.9762	1.0063
680_c	0.8836	0.9485	0.9111	0.9411

BUS ID	VOLTAGE (pu)			
	Without Capacitor	Decentralized Capcitor	Centralized Capacitor	
			At Bus-632	At Bus-680
692_a	0.9302	0.9877	0.9607	0.9813
692_b	0.9485	0.9914	0.9761	0.9949
692_c	0.8828	0.9477	0.9103	0.9295
675_a	0.9306	0.9869	0.9611	0.9816
675_b	0.9511	0.994	0.9786	0.9973
675_c	0.872	0.9355	0.8998	0.9192
684_a	0.9312	0.9888	0.9617	0.9822
684_c	0.8803	0.9473	0.9078	0.927
652_a	0.9294	0.987	0.9599	0.9803
611_c	0.877	0.9447	0.9045	0.9237

It can be seen that voltage level at some buses are much lower for the system without any external capacitor. As the distance increases from the bus-650, the voltage is reduced accordingly. This is due to the requirement of the higher reactive power and line loss of the system. To overcome this problem i.e. to improve the voltage, the external reactive power is needed. Hence the external capacitor is used for reactive power compensation in the system. The main purpose of this case study is the comparison between the Decentralized and Centralized methods for reactive power compensation in this 13 bus distribution system.

For the decentralized reactive power compensation method, 3 three-phase and 2 single-phase 200 kvar (in each phase) capacitors are connected at the different buses where the voltages is much lower. From the result of this simulation we can see that the voltage at that buses are improved. The total capacity of the capacitor is 2200 kvar in this decentralized method.

There are two different cases taken for the centralized reactive power compensation method for this system. In the first case, 1 three-phase capacitor of 700 kvar (in each phase) is connected at the bus-632 i.e. 2100 kvar total capacity. In the second case, 1 three-phase capacitor of 600 kvar (in each phase) is connected at the bus-680 i.e. 1800 kvar total capacity. The voltage at different buses are improved in each case.

Here the graphical comparison of voltages at different buses for 13 bus distribution system without capacitor, with decentralized capacitor and with centralized capacitor(case-1 & 2) is shown in Figure 3.2 .

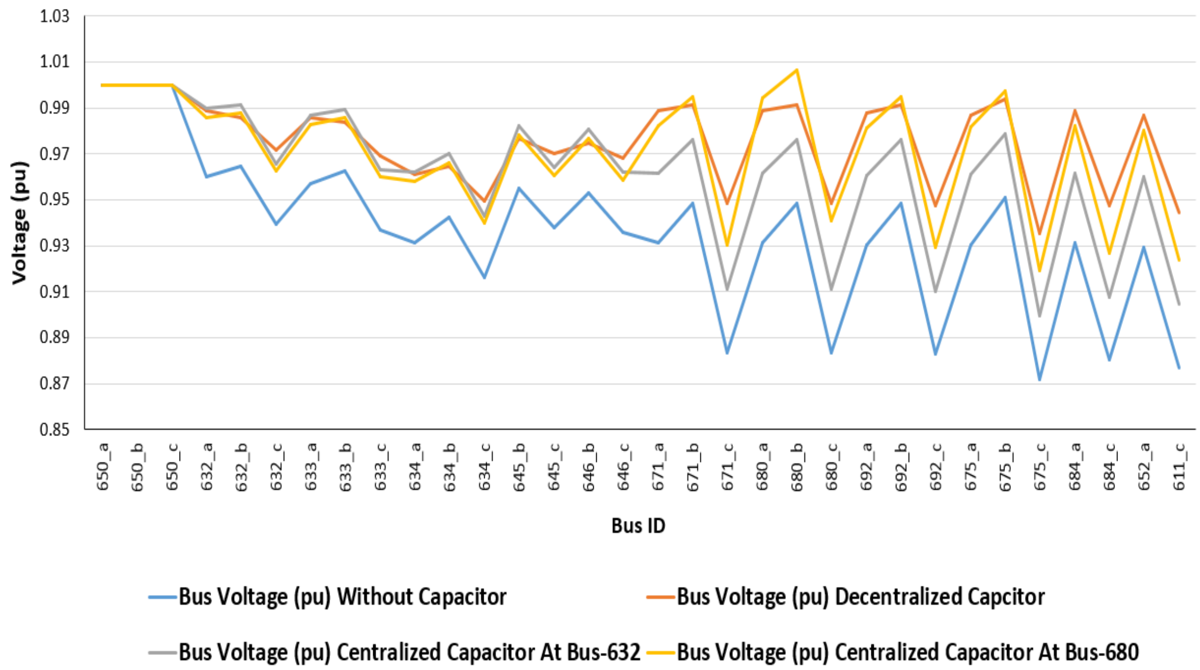


Figure 3.2: Comparison of Voltages for different cases

The voltage at different buses without capacitor, with decentralized capacitor, with centralized capacitor at bus-632 and with centralized capacitor at bus-680 are represented by the lines of Blue, Orange, Grey, and Yellow colour respectively. It can be seen from the graph that the voltage at bus-650 is remain constant at 1 pu for all the cases. The voltage at all the buses are improved with use of any type of reactive power compensation method.
The voltage is highly improved at weak buses for decentralized method as compare to centralized methods but the total capacity of capacitor is also much higher (2200 kvar) in decentralized method.
As comparing two centralized capacitor cases i.e. case 1 and case 2 ; The capacitor of total 2100 kvar capacity is connected at bus-632which is far from the weak buses in case 1 and the capacitor of total 1800 kvar capacity is connected at bus-680 which is near to the weak buses in case 2. The voltages at every buses are better and also the capacity of capacitor is lesser in case 2. This is because of the capacitor is connected near to the weak buses.

3.3.2 Power Loss

Total active and reactive power losses for this 13 bus distribution system without capacitor, with decentralized capacitor, with centralized capacitor (case 1 & 2) after load flow simulation are shown in Table 3.2.

Table 3.2: Power losses for different cases

	Total Power Losses			
	Without Capacitor	**Decentralized Capacitor**	**Centralized Capacitor**	
			At Bus-632	**At Bus-680**
Active loss P(kW)	143.70	101.84	116.64	112.77
Reactive loss Q(kvar)	410.07	282.99	324.19	309.42

The graphical representation of the active and reactive power losses without capacitor, with decentralized capacitor, with centralized capacitor (case 1 & 2) is shown in Figure 3.3 .

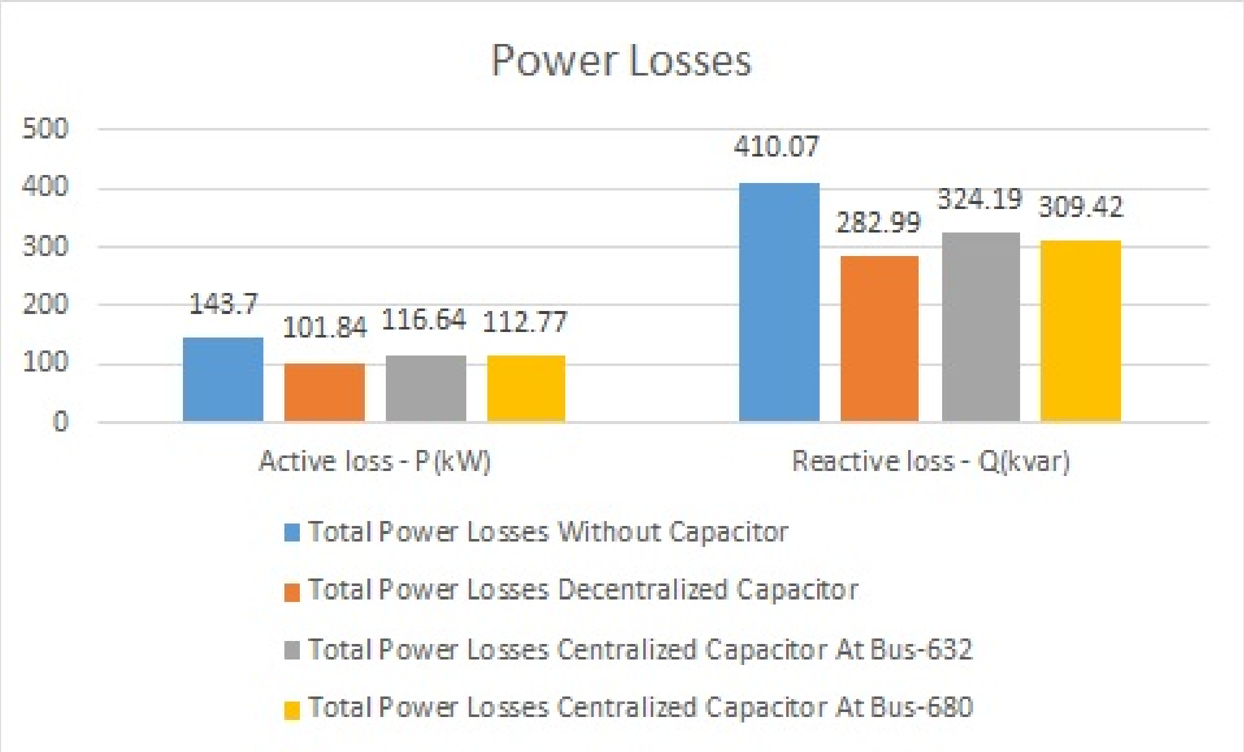


Figure 3.3: Comparison of Power losses for different cases

It can be seen that the active and reactive power losses are high in the distribution system without capacitor i.e. 143.7 kW and 410.07 kvar. The losses reduces as the reactive power compensation system is introduced by any of the methods.
As compared to centralized capacitor method, the losses are less in the decentralized capacitor method i.e. 101.84 kW and 282.99 kvar. This is because of the capacitors are connected nearer to the load. Also the large capacity of capacitor is used in decentralized case.
In centralized method there are two cases; the active and reactive power losses are 116.64 kW and 324.19 kvar for case 1 and 112.77 kW and 309.42 kvar for case 2 respectively. The improved results are given by case 2 along with lower capacity of capacitor.

Chapter 4

Optimization

4.1 Objective Function

The goal is to minimize the cost of the total real power loss and that of the shunt capacitor installation. So the objective function includes the cost of installed capacitor and cost of power loss. The cost function is given by

$F_i = K_C * Q_C + K_L * P_L$

K_C - Cost of capacitor (Rs/kvar)
Q_C - Capacity of installed capacitor (kvar)
K_L - Cost of active power loss (Rs/kW)
P_L - Active power loss (kW)

4.2 Constraints

4.2.1 Equality Constraint

The equality constraints are the power balance constraints with shunt capacitor. The active and reactive power must be balanced at generation and demand side. It can be formulated as:

$P_G = P_D + P_L$

$Q_G + Q_C = Q_D + Q_L$

P_G & Q_G - Active and Reactive power generation (kW and kvar)
P_D & Q_D - Active and Reactive power demand/load (kW and kvar)
P_L & Q_L - Active and Reactive power loss (kW and kvar)
Q_C - Capacity of installed capacitor (kvar)

4.2.2 Inequality Constraint

The inequality constraint is voltage level at every bus. Voltage limit includes the upper and lower voltage magnitude limits at each bus,which can be expressed as:

$V_{MIN} < V_I < V_{MAX}$

Where V_{MIN} and V_{MAX} are the minimum and maximum voltage limits respectively.

4.3 Algorithm

The algorithm steps for finding the minimum value of the objective function is as below.

- Step 1 : Take the new simulation case for the centralized compensation and run the load flow simulation.
- Step 2 : Store the result data of load flow simulation.
- Step 3 : Initialize the minimum value of objective function as infinity i.e. $F_{i(min)}$ = Inf.
- Step 4 : Check the equality and inequality constraints for that simulation case. If any of the constraints is not within limits, go to step 1.
- Step 5 : Find the value of objective function F_i.
- Step 6 : Check the value of objective function is minimum or not. If the value is minimum, show the result. If value is not minimum, go to step 1.

4.4 Flowchart

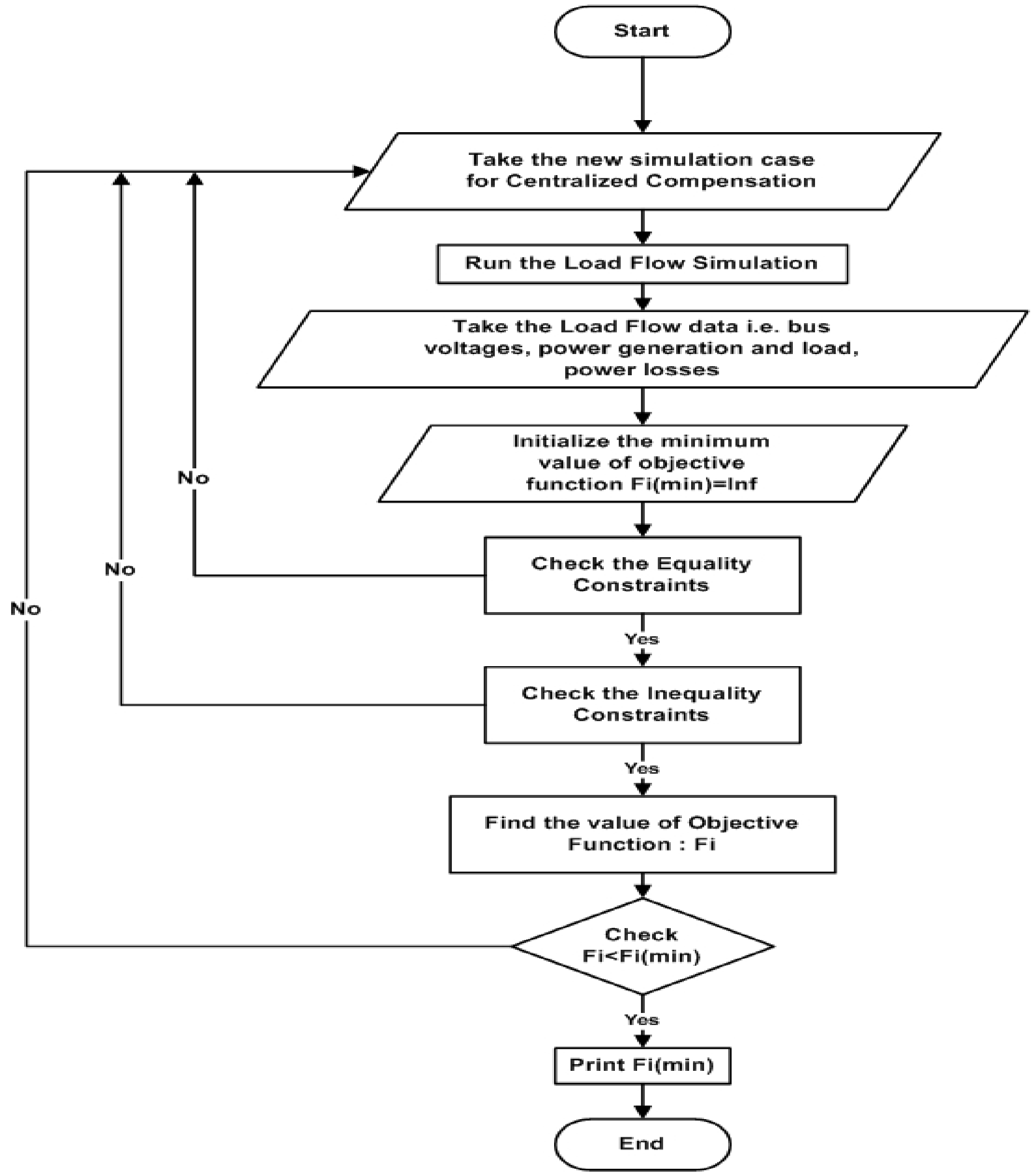


Figure 4.1: Flowchart to find the minimum value of objective function

Chapter 5

Comparative Results

The comparison between Centralized capacitor method and Decentralized capacitor method is done in this section.
For centralized capacitor method, five different cases are considered as below.

- 700 kvar (per phase) is connected to bus 680
- 700 kvar (per phase) is connected to bus 692
- 700 kvar (per phase) is connected to bus 671
- 700 kvar (per phase) is connected to bus 632
- 700 kvar (per phase) is connected to bus 633

The above five cases are compared with the Decentralized capacitor case which is mentioned in section 3.2.2. Different parameters are compared after load flow simulation of 13 bus distribution system on Matlab software.

5.1 Voltage and Cost comparison at different loading conditions

Voltage and Cost comparison for the above centralized and decentralized cases at different load conditions is done. The value of voltage at different buses are found after doing the load flow simulation on Matlab software for each cases. The value of cost for each case is found by suing the objective function discussed in section 4.1. The capacity of installed capacitor for reactive power compensation and the active power losses are included for finding the cost. The cost of capacitor K_C is taken constant as Rs 500 per kavr and the cost of active power loss K_L is taken constant as Rs 5 per kW.

5.1.1 Normal Loading

Above all cases of 13 bus distribution system are simulated with the normal loading condition. The data for the load is taken from the standard IEEE Test Feeder. The voltage and cost for above cases are compared as below.

Voltage Comparison

Bus voltages at each buses of 13 bus distribution system for above centralized and decentralized cases are shown in the Table 5.1.

Table 5.1: Voltage at different buses for normal loading

Bus ID	VOLTAGE (pu)					
	Centralized Capacitor					Decentralized Capacitor
	At 680	At 692	At 671	At 632	At 633	
650_a	1	1	1	1	1	1
650_b	1	1	1	1	1	1
650_c	1	1	1	1	1	1
632_a	0.9904	0.9899	0.9899	0.99	0.9901	0.9883
632_b	0.9916	0.9913	0.9913	0.9916	0.9917	0.9854
632_c	0.9659	0.9655	0.9656	0.9657	0.9658	0.9713
633_a	0.9874	0.9869	0.987	0.987	0.9937	0.9853
633_b	0.9897	0.9894	0.9894	0.9896	0.9992	0.9835
633_c	0.9632	0.9629	0.9629	0.963	0.971	0.9687
634_a	0.9627	0.9622	0.9623	0.9623	0.9691	0.9606
634_b	0.9704	0.9701	0.9701	0.9704	0.9802	0.9641
634_c	0.9434	0.9431	0.9431	0.9432	0.9514	0.949
645_b	0.9823	0.982	0.982	0.9823	0.9824	0.9761
645_c	0.9641	0.9638	0.9638	0.9639	0.964	0.9696
646_b	0.9806	0.9803	0.9803	0.9806	0.9808	0.9744
646_c	0.9622	0.9618	0.9618	0.962	0.962	0.9676
671_a	0.9916	0.9905	0.9906	0.9617	0.9618	0.9875
671_b	1.003	1.0024	1.0024	0.9762	0.9763	0.9908
671_c	0.937	0.9363	0.9363	0.9111	0.9112	0.9477
680_a	1.0061	0.9905	0.9906	0.9617	0.9618	0.9875
680_b	1.0163	1.0024	1.0024	0.9762	0.9763	0.9908
680_c	0.9498	0.9363	0.9363	0.9111	0.9112	0.9477
692_a	0.9906	0.9896	0.9897	0.9607	0.9608	0.9866
692_b	1.0029	1.0022	1.0023	0.9761	0.9762	0.9906
692_c	0.9363	0.9355	0.9356	0.9103	0.9104	0.947
675_a	0.991	0.99	0.9901	0.9611	0.9612	0.9858
675_b	1.0053	1.0046	1.0047	0.9786	0.9787	0.9933

Bus ID	VOLTAGE (pu)					
	Centralized Capacitor					Decentralized Capacitor
	At 680	At 692	At 671	At 632	At 633	
675_c	0.926	0.9253	0.9253	0.8998	0.8999	0.9348
684_a	0.9916	0.9905	0.9907	0.9617	0.9618	0.9877
684_c	0.9335	0.9327	0.9328	0.9078	0.9079	0.9466
652_a	0.9897	0.9887	0.9888	0.9599	0.96	0.9859
611_c	0.93	0.9292	0.9293	0.9045	0.9046	0.9439

The graphical comparison of voltage between all centralized capacitor cases with decentralized capacitor case for 13 bus distribution system is shown in figure 5.1.

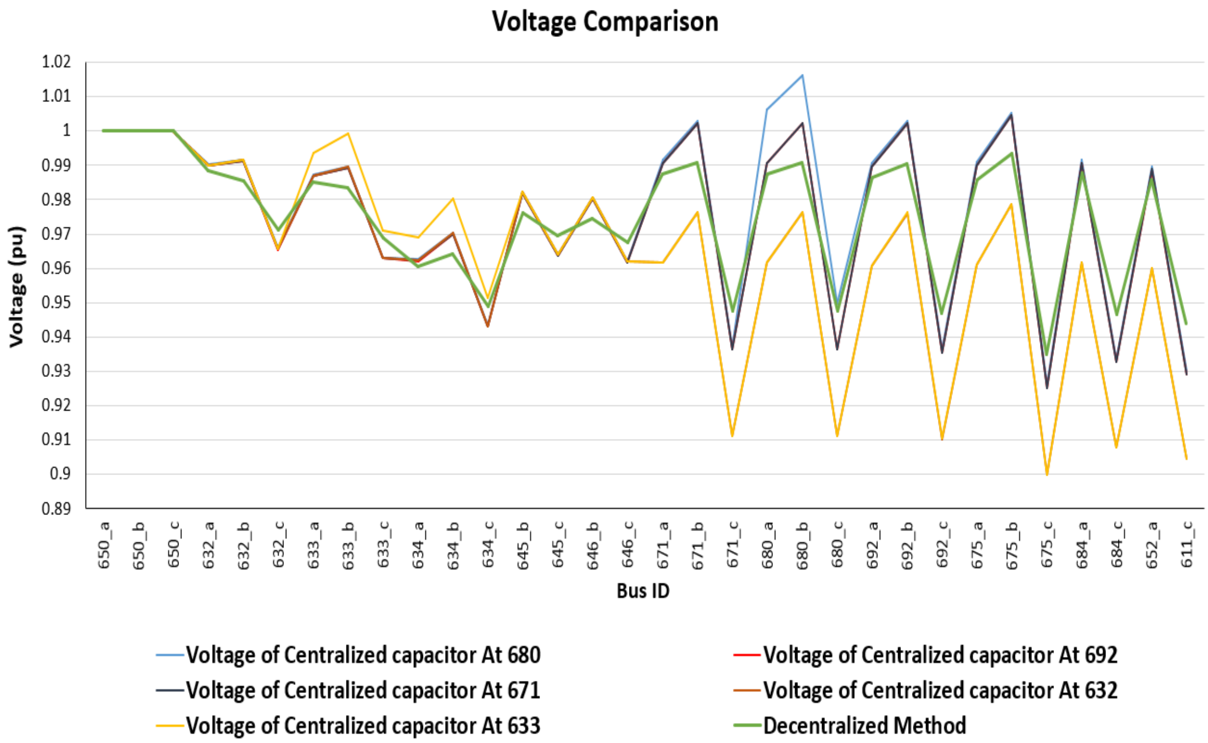


Figure 5.1: Voltage for normal loading

It can be seen that the voltage at different buses are within the limit between 0.935 to 1.00 pu when decentralized capacitor is used for reactive power compensation. This is shown by Green colour line in the figure.
While comparing centralized capacitor cases with this decentralized capacitor case, voltage at different buses are between 0.90 to 1.00 pu for two centralized capacitor cases i.e. capacitor is connected to bus-632 and capacitor is connected to bus-633. This is shown by Brown and Yellow colour line respectively. The voltage at buses connected to higher load are lower value in these both centralized capacitor cases.

Blue, Orange and Black colour line represent the voltage at different buses with centralized capacitor is connected to bus-680, bus-692 and bus-671 respectively. The value of voltage at different buses of these cases are nearer to that decentralized capacitor case. The voltage for the centralized cases at bus-692 and at bus-671 are between 0.925 to 1.002 pu. And the voltage at different buses for the centralized capacitor case at bus-680 are within limit between 0.926 to 1.016 pu.

Cost Comparison

The cost of above centralized and decentralized cases for 13 bus distribution system are shown in the Table 5.2.

Table 5.2: Cost comparison for Normal Loading

	Centralized Capacitor					**Decentralized Capacitor**
	At 680	**At 692**	**At 671**	**At 632**	**At 633**	
Cost	1050529.58	1050535.26	1050530.53	1050583.23	1050582.93	1100509.21

It can be seen that the cost of decentralized capacitor case is high as compare to all the centralized capacitor cases. The cost of decentralized capacitor case is Rs 1100509.21. There is less difference in cost among the centralized capacitor cases. The cost of centralized capacitor case at bus-632 and case at bus-633 are almost same amount i.e. Rs 1050583.23 and Rs 1050582.92 respectively. Also the cost of centralized capacitor case at bus-680, case at bus-692 and case at bus-671 are nearly same amount i.e. Rs 1050529.58, Rs 1050535.26 and Rs 1050530.53 respectively.

5.1.2 10% load increment in whole system

All cases of 13 bus distribution system are simulated with 10% load increment in whole distribution system. The voltage and cost for above centralized capacitor and decentralized capacitor cases for 10% load increment are compared in this section.

Voltage Comparison

Bus voltages at each buses of 13 bus distribution system with 10% load increment for above centralized and decentralized cases are shown in the Table 5.3.

Table 5.3: Voltage at different buses for 10% load increment

Bus ID	VOLTAGE (pu)					
	Centralized Capacitor					Decentralized Capacitor
	At 680	At 692	At 671	At 632	At 633	
650_a	1	1	1	1	1	1
650_b	1	1	1	1	1	1
650_c	1	1	1	1	1	1
632_a	0.9876	0.9871	0.9783	0.9873	0.9873	0.9856
632_b	0.989	0.9887	0.9807	0.9889	0.989	0.9828
632_c	0.9642	0.9639	0.956	0.9633	0.9634	0.9689
633_a	0.9845	0.984	0.9752	0.9842	0.9908	0.9825
633_b	0.9869	0.9866	0.9786	0.9868	0.9964	0.9807
633_c	0.9615	0.9611	0.9532	0.9606	0.9686	0.9661
634_a	0.9585	0.958	0.9489	0.9581	0.965	0.9564
634_b	0.9663	0.966	0.9578	0.9662	0.976	0.9599
634_c	0.9403	0.9399	0.9319	0.9394	0.9476	0.9451
645_b	0.9793	0.9789	0.9709	0.9791	0.9793	0.973
645_c	0.9625	0.9621	0.9543	0.9616	0.9617	0.9671
646_b	0.9775	0.9772	0.9692	0.9774	0.9775	0.9712
646_c	0.9605	0.9601	0.9523	0.9596	0.9597	0.9651
671_a	0.9861	0.9851	0.9675	0.9565	0.9566	0.9822
671_b	0.9993	0.9987	0.9827	0.9724	0.9725	0.987
671_c	0.9342	0.9334	0.9175	0.9069	0.907	0.9432
680_a	1.0006	0.9851	0.9675	0.9565	0.9566	0.9822
680_b	1.0126	0.9987	0.9827	0.9724	0.9725	0.987
680_c	0.9469	0.9334	0.9175	0.9069	0.907	0.9432
692_a	0.9852	0.9842	0.9666	0.9556	0.9557	0.9813
692_b	0.9992	0.9985	0.9826	0.9722	0.9724	0.9868
692_c	0.9334	0.9326	0.9167	0.9061	0.9062	0.9424
675_a	0.9856	0.9846	0.9669	0.9559	0.956	0.9805
675_b	1.0016	1.0009	0.985	0.9747	0.9749	0.9894

Bus ID	VOLTAGE (pu)					
	Centralized Capacitor					Decentralized Capacitor
	At 680	At 692	At 671	At 632	At 633	
675_c	0.9234	0.9227	0.9066	0.8959	0.896	0.9305
684_a	0.9861	0.985	0.9675	0.9565	0.9566	0.9824
684_c	0.9308	0.93	0.9141	0.9035	0.9036	0.9418
652_a	0.9842	0.9831	0.9656	0.9546	0.9547	0.9805
611_c	0.9273	0.9266	0.9107	0.9	0.9001	0.9391

The graphical comparison of voltage between all centralized capacitor cases with decentralized capacitor case for 13 bus distribution system with 10% load increment is shown in figure 5.2.

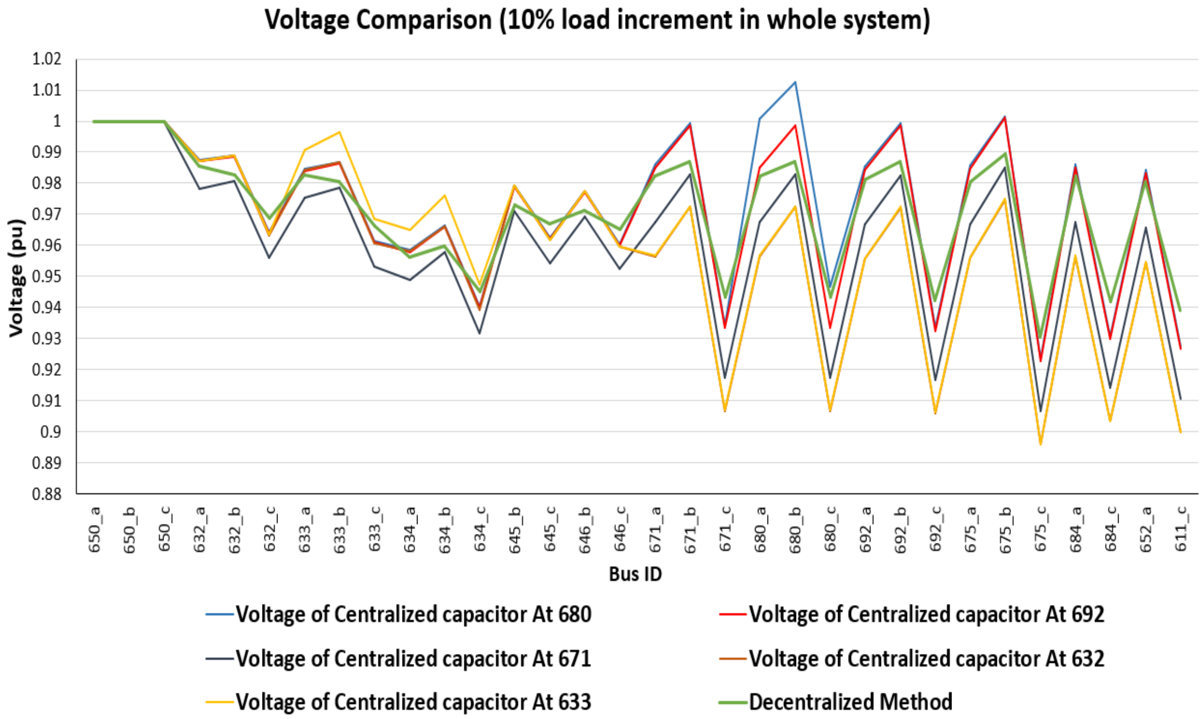


Figure 5.2: Voltage for 10% load increment

It can be seen that the voltage at different buses are within the limit between 0.930 to 1.00 pu when decentralized capacitor is used for reactive power compensation. This is shown by Green colour line in the figure. While comparing centralized capacitor cases with this decentralized capacitor case, voltage at different buses are between 0.895 to 1.00 pu for two centralized capacitor cases i.e. capacitor is connected to bus-632 and capacitor is connected to bus-633. This is shown by Brown and Yellow colour line respectively. The voltage at buses connected to higher load are lower value in these both centralized capacitor cases.

Also the voltage for centralized capacitor case at bus-671 is between 0.906 to 1.00 pu which is shown by Black colour line. Voltage for the centralized capacitor case at bus-680 and at bus-692 are shown by Blue and Orange colour lines respectively. It can be seen that these both lines are closed to the Green colour line. The voltage at different buses are within the limit between 0.923 to 1.012 pu and 0.922 to 1.00 pu respectively.

Cost Comparison

The cost of above centralized and decentralized cases for 13 bus distribution system with 10% load increment are shown in the Table 5.4.

Table 5.4: Cost comparison for 10% load increment

	Centralized Capacitor					**Decentralized Capacitor**
	At 680	**At 692**	**At 671**	**At 632**	**At 633**	
Cost	1050577.46	1050536.25	1050559.00	1050602.61	1050649.28	1100381.06

It can be seen that the cost of decentralized capacitor case is high as compare to all the centralized capacitor cases. The cost of decentralized capacitor case is Rs 1100381.06. The lowest cost among all centralized capacitor cases is Rs 1050536.25 which is for the case of centralized capacitor at bus-692. Also the cost for other centralized cases at bus-680, at bus-671, at bus-632 and at bus-633 are Rs 1050577.46, Rs 1050559.00, Rs 1050602.61, and Rs 1050649.28 respectively.

5.1.3 20% load increment in whole system

All cases of 13 bus distribution system are simulated with 20% load increment in whole distribution system. The voltage and cost for above centralized capacitor and decentralized capacitor cases for 20% load increment are compared in this section.

Voltage Comparison

Bus voltages at each buses of 13 bus distribution system with 20% load increment for above centralized and decentralized cases are shown in the Table 5.5.

Table 5.5: Voltage at different buses for 20% load increment

Bus ID	**VOLTAGE (pu)**					
	Centralized Capacitor					**Decentralized Capacitor**
	At 680	**At 692**	**At 671**	**At 632**	**At 633**	
650_a	1	1	1	1	1	1
650_b	1	1	1	1	1	1
650_c	1	1	1	1	1	1
632_a	0.9845	0.984	0.9752	0.9842	0.9843	0.9824
632_b	0.9873	0.987	0.979	0.9873	0.9873	0.9811
632_c	0.9591	0.9588	0.9509	0.9579	0.9583	0.9636
633_a	0.9813	0.9807	0.9719	0.9809	0.9875	0.9792
633_b	0.9851	0.9848	0.9768	0.9851	0.9945	0.9788
633_c	0.9563	0.9559	0.948	0.955	0.9633	0.9608
634_a	0.9534	0.9529	0.9438	0.9531	0.9599	0.9513
634_b	0.9635	0.9631	0.955	0.9634	0.9731	0.9571
634_c	0.9339	0.9336	0.9255	0.9326	0.9411	0.9386
645_b	0.9771	0.9768	0.9687	0.9771	0.9771	0.9708
645_c	0.9574	0.957	0.9492	0.9561	0.9565	0.9618
646_b	0.9753	0.9749	0.9669	0.9752	0.9753	0.969
646_c	0.9554	0.955	0.9472	0.9541	0.9545	0.9598
671_a	0.9805	0.9794	0.9619	0.951	0.951	0.9764
671_b	0.9974	0.9967	0.9808	0.9708	0.9707	0.985
671_c	0.9241	0.9234	0.9074	0.8962	0.8969	0.9328
680_a	0.9948	0.9794	0.9619	0.951	0.951	0.9764
680_b	1.0106	0.9967	0.9808	0.9708	0.9707	0.985
680_c	0.9367	0.9234	0.9074	0.8962	0.8969	0.9328
692_a	0.9795	0.9785	0.9609	0.9501	0.9501	0.9755
692_b	0.9972	0.9966	0.9807	0.9706	0.9706	0.9849
692_c	0.9233	0.9226	0.9066	0.8954	0.8961	0.932
675_a	0.9801	0.9791	0.9615	0.9507	0.9507	0.9749
675_b	0.9998	0.9992	0.9833	0.9734	0.9733	0.9877

Bus ID	VOLTAGE (pu)					
	Centralized Capacitor					Decentralized Capacitor
	At 680	At 692	At 671	At 632	At 633	
675_c	0.9134	0.9126	0.8965	0.8851	0.8859	0.9201
684_a	0.9804	0.9793	0.9618	0.951	0.951	0.9767
684_c	0.9206	0.9199	0.9039	0.8927	0.8934	0.9313
652_a	0.9784	0.9774	0.9599	0.9491	0.9491	0.9747
611_c	0.9171	0.9164	0.9004	0.8892	0.8899	0.9284

The graphical comparison of voltage between all centralized capacitor cases with decentralized capacitor case for 13 bus distribution system with 20% load increment is shown in figure 5.3.

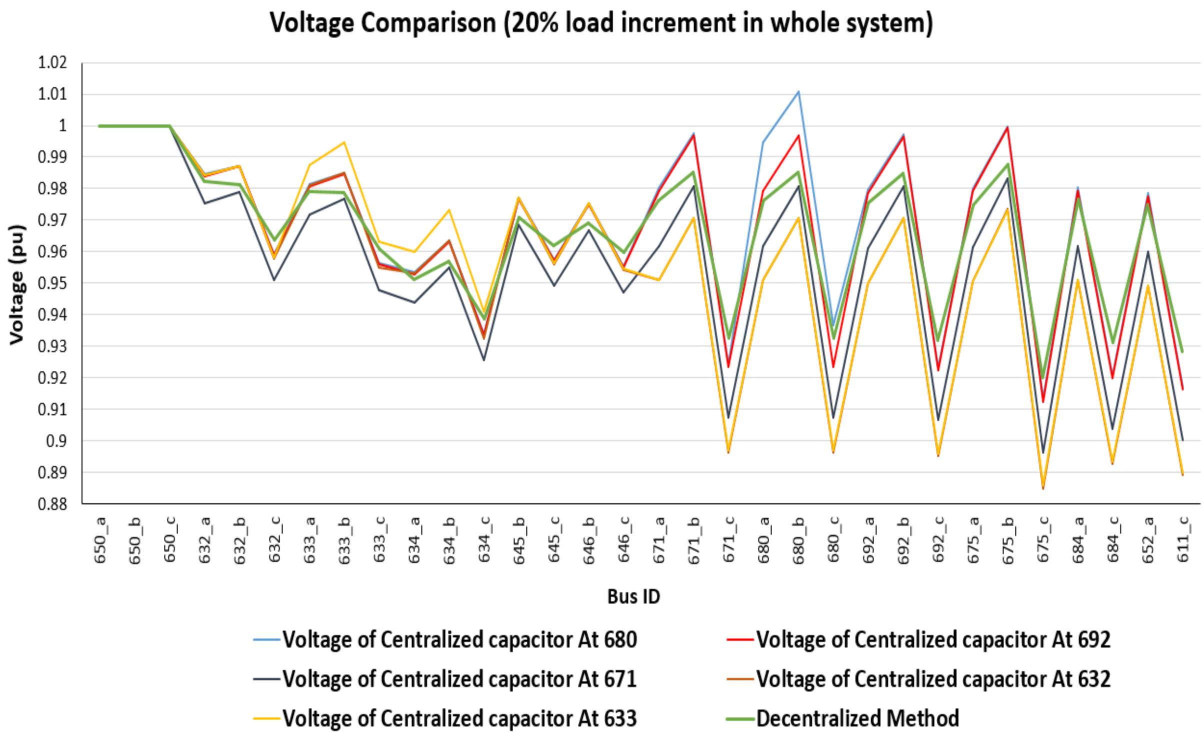


Figure 5.3: Voltage for 20% load increment

It can be seen that the voltage at different buses are within the limit between 0.920 to 1.00 pu when decentralized capacitor is used for reactive power compensation. This is shown by Green colour line in the figure. While comparing centralized capacitor cases with this decentralized capacitor case, voltage at different buses are between 0.885 to 1.00 pu for two centralized capacitor cases i.e. capacitor is connected to bus-632 and capacitor is connected to bus-633. This is shown by Brown and Yellow colour line respectively. The voltage at buses connected to higher load are lower value in these both centralized capacitor cases. Also the voltage for centralized capacitor case at bus-671 is between 0.896 to 1.00 pu which is shown by Black colour line. It can be seen that the Black colour line is below than the Green colour line for all the buses. Voltage for the centralized capacitor case at bus-680 and at bus-692 are shown by Blue and Orange colour lines respectively. It can be seen that these both lines are closed to the Green colour line. The voltage at different buses are within the limit between 0.913 to 1.010 pu and 0.912 to 1.00 pu respectively.

Cost Comparison

The cost of above centralized and decentralized cases for 13 bus distribution system with 20% load increment are shown in the Table 5.6.

Table 5.6: Cost comparison for 20% load increment

	Centralized Capacitor					**Decentralized Capacitor**
	At 680	**At 692**	**At 671**	**At 632**	**At 633**	
Cost	1050596.00	1050554.81	1050591.07	1050641.59	1050683.79	1100533.63

It can be seen that the cost of decentralized capacitor case is high as compare to all the centralized capacitor cases. The cost of decentralized capacitor case is Rs 1100533.63. The lowest cost among all centralized capacitor cases is Rs 1050554.81 which is for the case of centralized capacitor at bus-692. Also the cost for other centralized cases at bus-680, at bus-671, at bus-632 and at bus-633 are Rs 1050596.00, Rs 1050591.07, Rs 1050641.59, and Rs 1050683.79 respectively.

5.1.4 25% load increment in whole system

All cases of 13 bus distribution system are simulated with 25% load increment in whole distribution system. The voltage and cost for above centralized capacitor and decentralized capacitor cases for 25% load increment are compared in this section.

Voltage Comparison

Bus voltages at each buses of 13 bus distribution system with 25% load increment for above centralized and decentralized cases are shown in the Table 5.7.

Table 5.7: Voltage at different buses for 25% load increment

Bus ID	**VOLTAGE (pu)**					
	Centralized Capacitor					**Decentralized Capacitor**
	At 680	**At 692**	**At 671**	**At 632**	**At 633**	
650_a	1	1	1	1	1	1
650_b	1	1	1	1	1	1
650_c	1	1	1	1	1	1
632_a	0.9831	0.9815	0.9738	0.9827	0.9828	0.981
632_b	0.9862	0.9804	0.9779	0.9861	0.9862	0.98
632_c	0.957	0.971	0.9487	0.956	0.9561	0.9623
633_a	0.9798	0.9782	0.9704	0.9794	0.9861	0.9777
633_b	0.984	0.9781	0.9756	0.9838	0.9934	0.9778
633_c	0.954	0.9681	0.9458	0.9531	0.961	0.9594
634_a	0.9514	0.9498	0.9418	0.951	0.9579	0.9492
634_b	0.9617	0.9557	0.9531	0.9615	0.9713	0.9553
634_c	0.931	0.9454	0.9225	0.93	0.9382	0.9365
645_b	0.9758	0.9699	0.9675	0.9757	0.9758	0.9696
645_c	0.9552	0.9692	0.947	0.9543	0.9544	0.9606
646_b	0.9739	0.968	0.9656	0.9738	0.9739	0.9677
646_c	0.9532	0.9672	0.945	0.9523	0.9524	0.9585
671_a	0.9776	0.9738	0.959	0.9482	0.9482	0.9736
671_b	0.996	0.9846	0.9794	0.9692	0.9694	0.9838
671_c	0.92	0.9481	0.9033	0.8928	0.8929	0.9305
680_a	0.9919	0.9738	0.959	0.9482	0.9482	0.9736
680_b	1.0092	0.9846	0.9794	0.9692	0.9694	0.9838
680_c	0.9326	0.9481	0.9033	0.8928	0.8929	0.9305
692_a	0.9767	0.9729	0.9581	0.9472	0.9473	0.9727
692_b	0.9959	0.9845	0.9793	0.9691	0.9693	0.9837
692_c	0.9192	0.9474	0.9025	0.892	0.8921	0.9297
675_a	0.9773	0.9717	0.9587	0.9479	0.9479	0.9721
675_b	0.9985	0.9859	0.982	0.9719	0.972	0.9865

Bus ID	VOLTAGE (pu)					
	Centralized Capacitor					Decentralized Capacitor
	At 680	At 692	At 671	At 632	At 633	
675_c	0.9094	0.9388	0.8925	0.8818	0.8819	0.9178
684_a	0.9775	0.9738	0.9589	0.9481	0.9482	0.9737
684_c	0.9165	0.9444	0.8998	0.8893	0.8893	0.9292
652_a	0.9756	0.9718	0.957	0.9462	0.9463	0.9718
611_c	0.9129	0.9406	0.8962	0.8857	0.8858	0.9265

The graphical comparison of voltage between all centralized capacitor cases with decentralized capacitor case for 13 bus distribution system with 25% load increment is shown in figure 5.3.

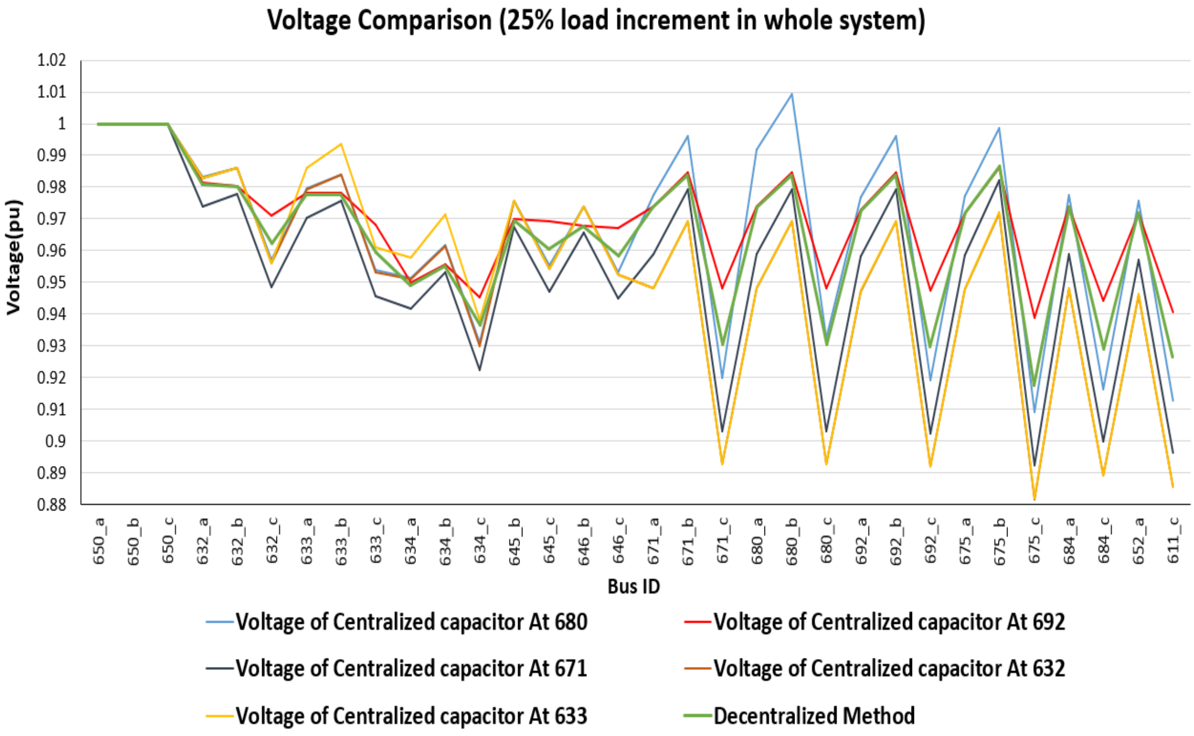


Figure 5.4: Voltage for 25% load increment

It can be seen that the voltage at different buses are within the limit between 0.917 to 1.00 pu when decentralized capacitor is used for reactive power compensation. This is shown by Green colour line in the figure. While comparing centralized capacitor cases with this decentralized capacitor case, voltage at different buses are between 0.881 to 1.00 pu for two centralized capacitor cases i.e. capacitor is connected to bus-632 and capacitor is connected to bus-633. This is shown by Brown and Yellow colour line respectively. The voltage at buses connected to higher load are lower value in these both centralized capacitor cases.

Also the voltage for centralized capacitor case at bus-671 is between 0.892 to 1.00 pu which is shown by Black colour line. It can be seen that the Black colour line is below than the Green colour line for all the buses. The voltage at different buses are between 0.919 to 1.00 pu for the centralized capacitor case at bus-680. This is shown by the Blue colour line.
The best voltage profile is seen by the centralized capacitor case at bus-692 which is shown by Orange colour line in the figure. Orange colour line has given better voltage at every buses in the system than the Green colour line. The voltage at different buses are between 0.938 to 1.00 pu for this case. So the centralized capacitor case at bus-692 has given better voltage than the decentralized capacitor case for 25% load increment.

Cost Comparison

The cost of above centralized and decentralized cases for 13 bus distribution system with 25% load increment are shown in the Table 5.8.

Table 5.8: Cost comparison for 25% load increment

	Centralized Capacitor					**Decentralized Capacitor**
	At 680	**At 692**	**At 671**	**At 632**	**At 633**	
Cost	1050605.56	1050531.48	1050606.87	1050658.00	1050700.52	1100536.40

It can be seen that the cost of decentralized capacitor case is high as compare to all the centralized capacitor cases. The cost of decentralized capacitor case is Rs 1100536.40. Also the lowest cost among all centralized capacitor cases is given by the case at bus-692 i.e. Rs 1050531.48. The cost for other centralized cases at bus-680, at bus-671, at bus-632 and at bus-633 are Rs 1050605.56, Rs 1050606.87, Rs 1050658.00, and Rs 1050700.52 respectively.

5.1.5 50% load increment in whole system

All cases of 13 bus distribution system are simulated with 50% load increment in whole distribution system. The voltage and cost for above centralized capacitor and decentralized capacitor cases for 50% load increment are compared in this section.

Voltage Comparison

Bus voltages at each buses of 13 bus distribution system with 50% load increment for above centralized and decentralized cases are shown in the Table 5.9.

Table 5.9: Voltage at different buses for 50% load increment

Bus ID	VOLTAGE (pu)					
	Centralized Capacitor					Decentralized Capacitor
	At 680	At 692	At 671	At 632	At 633	
650_a	1	1	1	1	1	1
650_b	1	1	1	1	1	1
650_c	1	1	1	1	1	1
632_a	0.9757	0.9752	0.9664	0.9754	0.9755	0.9737
632_b	0.9808	0.9805	0.9725	0.9806	0.9808	0.9746
632_c	0.9471	0.9467	0.9388	0.9461	0.9462	0.9524
633_a	0.9721	0.9716	0.9627	0.9717	0.9783	0.97
633_b	0.9782	0.9779	0.9699	0.9781	0.9875	0.972
633_c	0.9439	0.9435	0.9356	0.9429	0.9507	0.9492
634_a	0.9398	0.9393	0.9301	0.9394	0.9463	0.9376
634_b	0.9529	0.9526	0.9444	0.9528	0.9625	0.9466
634_c	0.9176	0.9173	0.9091	0.9166	0.9247	0.9232
645_b	0.9692	0.9689	0.9609	0.9691	0.9693	0.963
645_c	0.9453	0.945	0.9371	0.9443	0.9444	0.9507
646_b	0.9671	0.9668	0.9588	0.967	0.9672	0.9609
646_c	0.9433	0.943	0.9351	0.9423	0.9424	0.9486
671_a	0.9638	0.9628	0.9452	0.9346	0.9347	0.9598
671_b	0.9888	0.9882	0.9723	0.9623	0.9625	0.9767
671_c	0.901	0.9002	0.8842	0.8738	0.8739	0.9114
680_a	0.9779	0.9628	0.9452	0.9346	0.9347	0.9598
680_b	1.0018	0.9882	0.9723	0.9623	0.9625	0.9767
680_c	0.9133	0.9002	0.8842	0.8738	0.8739	0.9114
692_a	0.9629	0.9619	0.9443	0.9337	0.9337	0.9589
692_b	0.9887	0.988	0.9722	0.9622	0.9624	0.9766
692_c	0.9001	0.8994	0.8833	0.873	0.8731	0.9106
675_a	0.9638	0.9628	0.9452	0.9346	0.9347	0.9586
675_b	0.9916	0.991	0.9752	0.9652	0.9654	0.9797

Bus ID	VOLTAGE (pu)					
	Centralized Capacitor					Decentralized Capacitor
	At 680	At 692	At 671	At 632	At 633	
675_c	0.8906	0.8899	0.8737	0.8632	0.8633	0.8991
684_a	0.9636	0.9626	0.9451	0.9345	0.9346	0.9598
684_c	0.8972	0.8965	0.8804	0.8701	0.8702	0.9098
652_a	0.9616	0.9606	0.9431	0.9325	0.9326	0.9578
611_c	0.8934	0.8926	0.8766	0.8662	0.8663	0.9068

The graphical comparison of voltage between all centralized capacitor cases with decentralized capacitor case for 13 bus distribution system with 50% load increment is shown in figure 5.4.

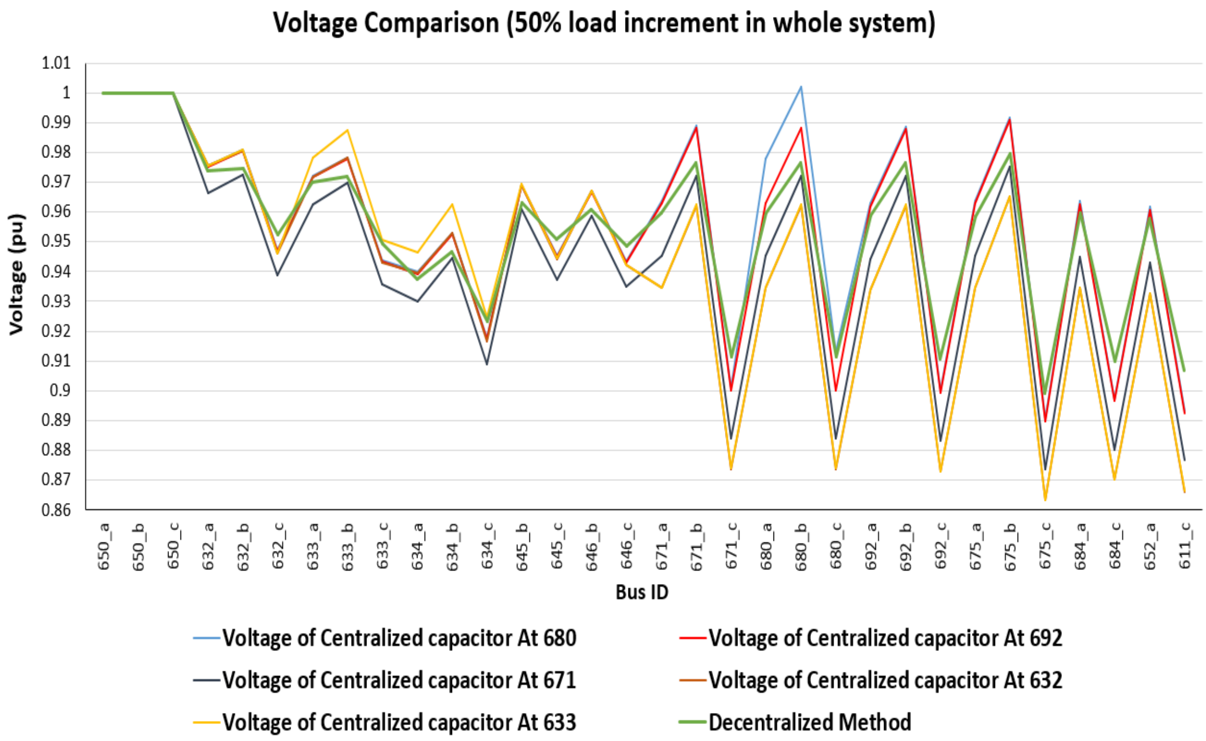


Figure 5.5: Voltage for 50% load increment

It can be seen that the voltage at different buses are within the limit between 0.899 to 1.00 pu when decentralized capacitor is used for reactive power compensation. This is shown by Green colour line in the figure. While comparing centralized capacitor cases with this decentralized capacitor case, voltage at different buses are between 0.863 to 1.00 pu for two centralized capacitor cases i.e. capacitor is connected to bus-632 and capacitor is connected to bus-633. This is shown by Brown and Yellow colour line respectively. The voltage at buses connected to higher load are lower value in these both centralized capacitor cases. Also the voltage for centralized capacitor case at bus-671 is between 0.973 to 1.00 pu which is shown by Black colour line. Voltage for the centralized capacitor case at bus-680 and at bus-692 are shown by Blue and Orange colour lines respectively. It can be seen that these both lines are closed to the Green colour line. The voltage at different buses are within the limit between 0.890 to 1.001 pu and 0.889 to 1.00 pu respectively.

Cost Comparison

The cost of above centralized and decentralized cases for 13 bus distribution system with 50% load increment are shown in the Table 5.10.

Table 5.10: Cost comparison for 50% load increment

	Centralized Capacitor					**Decentralized Capacitor**
	At 680	**At 692**	**At 671**	**At 632**	**At 633**	
Cost	1050668.55	1050627.88	1050700.15	1050761.39	1050797.13	1100596.29

It can be seen that the cost of decentralized capacitor case is high as compare to all the centralized capacitor cases. The cost of decentralized capacitor case is Rs 1100596.29. The lowest cost among all centralized capacitor cases is Rs 1050627.88 which is for the case of centralized capacitor at bus-692. Also the cost for other centralized cases at bus-680, at bus-671, at bus-632 and at bus-633 are Rs 1050668.55, Rs 1050700.15, Rs 1050761.39, and Rs 1050797.13 respectively.

Chapter 6

Conclusion

Different load flow simulations of the 13 bus distribution system are done with using decentralized capacitor and centralized capacitor method on Matlab software. Also different load conditions i.e. normal loading, 10% load increment, 20% load increment, 25% load increment, 50% load increment are considered for all the simulation cases. The 13 bus distribution system with centralized capacitor of 700 kvar (pre phase) at bus-692 have given overall better result of voltage at different buses with the lowest cost for every loading condition.

Chapter 7

Future Scope

- The protection system of the centralized capacitor would be implemented.
- Same type of implementation would be given to the larger distribution system.

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