MITIGATION OF VOLTAGE VIOLATIONS IN JAFFNA PENINSULA DISTRIBUTION SYSTEMS

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DECLARATION

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ABSTRACT

Mitigation of voltage violations are always a challenging task in distribution networks. Because the distribution networks are directly connected to the consumer loads, which are continuously varying. Under voltage and over voltage, voltage sag, swell and transients/fast variations are the voltage violations that limit the expansion of the electrical distribution networks. This can be eliminated by a step by step systematic approach/methods while providing a cost effective solution. Few examples are use of de-energized tap changer, on-load tap changer and the STATCOM to improve the performance of the distribution system.

This thesis presents the work of studying voltage violations in distribution systems and the case study was done with Jaffna peninsula electrical distribution system. The full day load pattern showed voltage problem in some bus bars especially during peak load conditions. Solutions are proposed, and healthy operation are validated using PACAD simulations to overcome the said problems.

Further a simple network was modelled to study the OLTC operations and a control system was developed to achieve the best customized operation to avoid voltage violation.

Considering the future development of Sri Lanka’s potential renewable energy development, the STATCOM applications were studied to eliminate the fast variations in the voltage. A STATCOM detail model using IGBT switches and a small scale distribution network were modelled. STATCOM converter control, AC terminal voltage droop control and DC-Link voltage regulatory control were designed to study the performance of the network on eliminating the voltage violations during the transient operations or fast variations on voltage. This was studied under the STATCOM control and its integrated applications together with the OLTC.

The study proposed three methods to mitigate voltage violations in distribution system network. This was done using de-energized tap changer, on-load tap changer and the STATCOM to improve the performance of the distribution system network. And it is validated using simulation results.

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LIST OF ABBREVIATIONS

BRK	Breaker
DETC	De-Energized Tap Changers
IGBT	Insulated Gate Bipolar Transistor
OLTC	On Load Tap Changers
PLL	Phase Lock Loop
PSCAD	Power System Computer Aided Design
pu	Per Unit
STATCOM	Static Synchronous Compensator
SVC	Static Var Compensator
BSC	Breaker Switched Capacitor

1

Introduction

1.1. Voltage violations in the distribution network

Increasing load creates challenges in the distribution system operation. Voltage violations in distribution networks are one of the major challenges that a distribution network commonly faces. Under voltage and over voltage, voltage sag, swell and transients/fast variations are the voltage violations which also limit the expansion of distribution system network.

1.1.1 Under voltage and Over voltage

As per IEEE classification, under voltage and over voltage are considered under long duration variations. This means the magnitude of the typical voltage in between 0.8-0.9 pu, more than a duration of I minute is considered as under voltage. On the other hand when the magnitude of the typical voltage in between 1.1-1.2 pu, more than a duration of I minute is considered as over voltage. This is shown in figure 1.1.

1.1.2 Voltage sag, Voltage swell and interruption

As per IEEE classification, voltage sag, voltage swell are considered under short duration variations. The magnitude of the typical voltage in between 0.1-0.9 pu, for a duration of 0.5 cycles to I minute is considered as voltage sag (dip). On the other hand when the magnitude of the typical voltage above 1.1 pu, for a duration of0.5 cycles to I minute is considered as voltage swell. This is shown in figure 1.1.

1.1.3 Voltage Transients

Any fast variations less than a period of 0.5 cycles can be considered as transients. This is shown in figure 1.1.

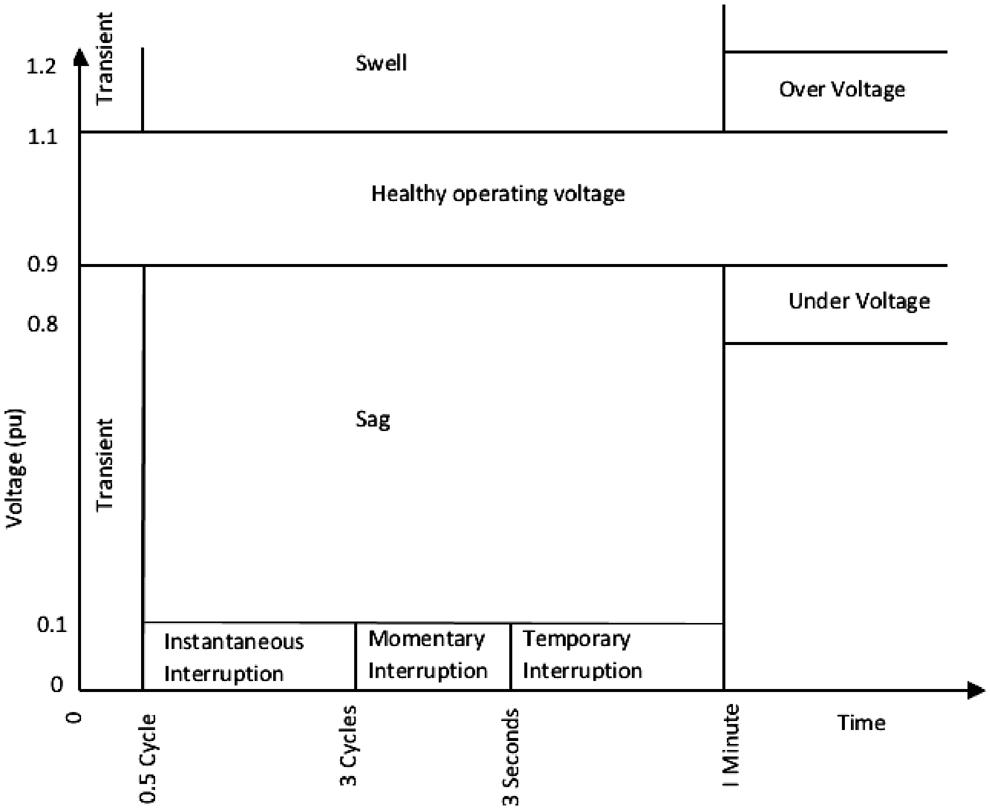


Figure 1.1 Voltage disturbances as per IEEE classification.

1.2 Voltage issue in Jaffna peninsula

From the literature review [1], it is identified that Jaffna peninsula electrical distribution network is interconnected with the Sri Lankan transmission network through long transmission lines. This may cause voltage violations. More than that rapid increase in load also may create under voltage challenges, therefore a case study on these issues is timely effort.

This is an off-line operational study with its available components, how it can be operated through proactive coordination based set values. Actually for this study the equivalent circuit of the Jaffna peninsula distribution network was considered. This is to avoid any confusion with Ceylon Electricity Board (CEB) in future.

Further, this method of study with existing devices and pre-set operations will tremendously reduce the cost for rehabilitation or new construction of the distribution network. Because this study push the distribution network devices' operating capacity up to its full ratings thus the maximum usage of this network and devices can be obtained. This reduces frequent new construction and as a result the total cost can be reduced. This also motivates that any industrial problems, studied through the applied research and development program will be the best solution to operate their system to the full capacity for its operations with good reliability.

1.3 Objectives

To identify methods to mitigate voltage violations in distribution system networks without violating the standards.

The methods used here are below.

a. Using De-Energized Tap Changer (DETC) {Fixed Tap method}
b. Using On Load Tap Changer (OLTC)
c. Using Static Synchronous Compensator (STATCOM)

When the voltage deviate from the standard, that is when under or over voltage violations observed, various methods used to manage the voltage to keep within the standard limits. They are:

- Usage of transformer De-Energized Tap Changers (DETC) {Fixed Tap Method}.
- Usage of transformer On Load Tap Changers (OLTC).

To mitigate under and over voltage issues, changing the cable type and increase the number of circuits techniques are also used. But they are considerably involve with cost and time.

Further to the above two method a third method also used to mitigate voltage violations in distribution system networks. That is

- Usage of Static Synchronous compensator (STATCOM).

But this method is primarily used for the study of fast variation or transients voltage issues. But from literatures, it is realized that the STATCOM is more economical only when it is required for eliminating fast variations in the voltage.

The STATCOM study was done as it will be required in the future. Because Sri Lanka has huge potential for electricity generation from the renewable energy technologies.

1.4 Overview of the thesis

Chapter 2 reviews the modeling and study the performance of a distribution system network. Here Jaffna peninsula distribution system network was taken for case study. The voltage violations were identified

Chapter 3 reviews the proposed solutions to mitigate voltage violations identified in chapter 2.
Section 3.1 describe the general methods used to solve the voltage violations that is utilize the fixed tap transformer (De-Energized Tap Changer). Equations are derived to calculate the transformer tap value to bring the transformer output voltage to safe middle region.

Section 3.2 reviews the usage of on load tap changer (OLTC) for distribution system network. As Jaffna distribution system network is not suitable to study the OLTC operation. A simple network was studied with OLTC operation.

Section 3.3 reviews the viability of STATCOM for solving problems in a distribution system network. A simple network was used to study the STATCOM performance of mitigating voltage violations.

Chapter 4 reviews the Performance of Jaffna distribution network together with STATCOM & OLTC

Chapter 5reviews the conclusion of the thesis.

2

Modeling and studying the performance of Jaffna distribution network

This chapter introduces the single line diagram of the equivalent circuit of Jaffna peninsula distribution network and the modeling of the network in PSCAD simulation. This network was studied for steady state voltage violation issues.

2.1 Single line diagram of the equivalent circuit of the Jaffna peninsula distribution network

Here the single line diagram represent the equivalent circuit of the Jaffna peninsula distribution network. This equivalent circuit primarily consider the 33kV system and also the secondary side of the 33/11kV step-down transformers. The Kilinochchi outgoing feeders, which is a double circuit 132kV transmission line towards Chunnakam substation. This is considered with a voltage source with equivalent internal impedance of its fault level. This lines are connected to the Chunnakam substation through 132/33kV step-down transformers. There are two transformers each capacity of 31.5MVA.

There are primary substations such as Parameswara primary, Kompayan primary and Ponnalai primary which are shown in boxes with dash lines.More than that Uthuru Janani generator is connected to the Chunnakam substation 33kV bus through step up transformers.

The distribution lines from Chunnakam substations are named Feeder 1, Feeder2 . . .. . to Feeder 13. Figure 2.1 shows the single line diagram of the above mentioned equivalent circuit.

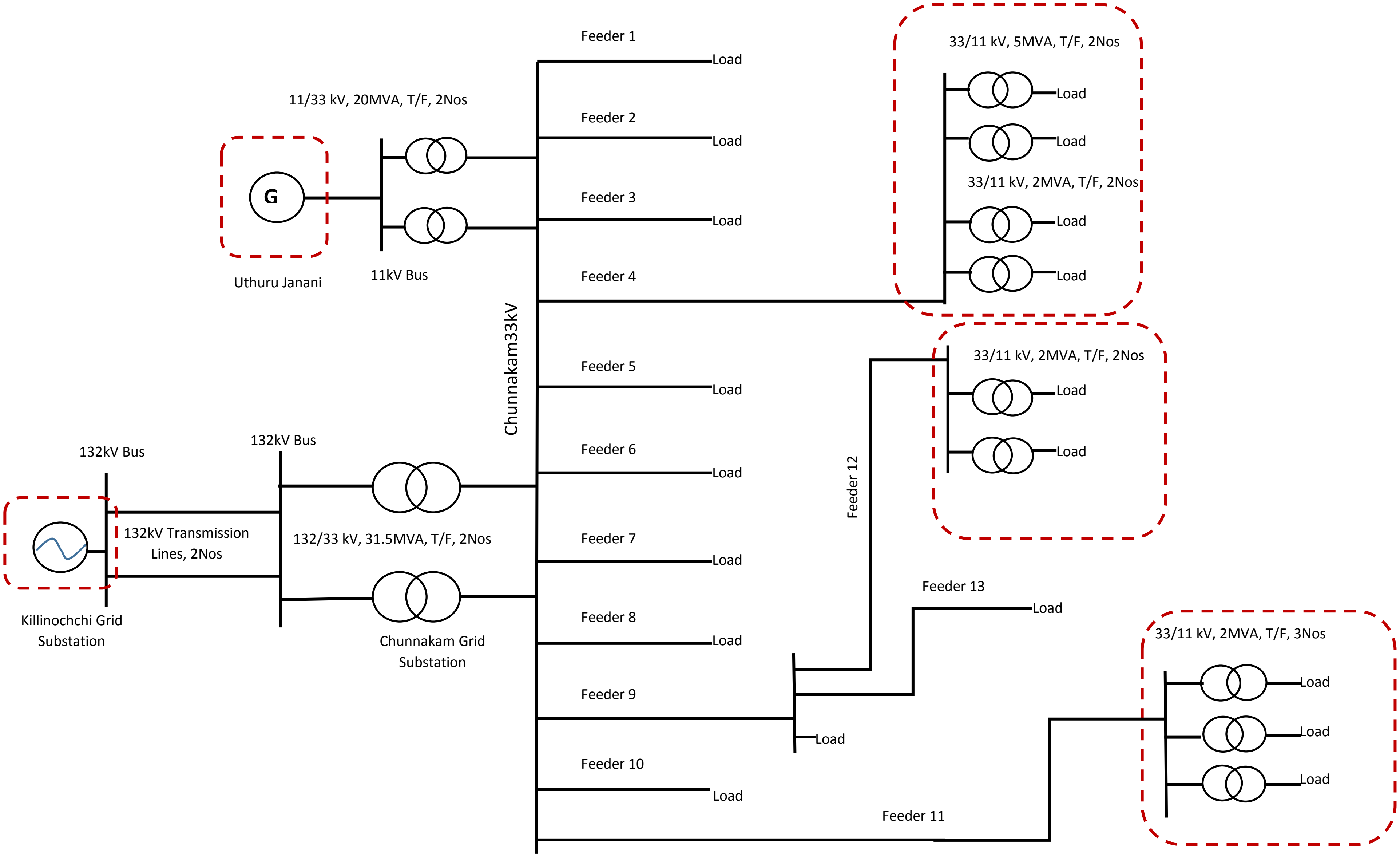


Figure 2.1: Single line diagram of the equivalent circuit of Jaffna peninsula distribution network

2.2 System Modeling

The above system is modeled using PSCAD simulation package.

2.2.1 Lines

Distributions lines play a major role to deliver the power to the consumer while keeping the voltage magnitude within standard limit. Here to study the performance of the distribution lines PS-CAD Bergeron model was used to model various electrical distribution lines.

The double circuit Zebra ACSR 132kV transmission line from Killinochchi to Chunnakam substation also was modeled using PS-CAD Bergeron model. But as mention in the single line diagram these transmission lines model considered with a voltage source at Killinochchi, with equivalent internal impedance of its fault level.

There are eleven outgoing feeders from Chunnakam power distribution station were included in the model. The line length of the distribution lines for the Bergeron model were considered the line length up to the half current locations of the distribution line. But the length of the 132kV line from Killinochchi to Chunnakam substation 67.2km the actual line length was taken for modeling. The line length of the cables for the primary substations are also taken the actual length of the cables at the existing network.

The cable parameters were referenced from the conductor characteristic chart for bare conductor that is given in the “Constructions standard for Medium voltage power distribution lines: - CEB-DCS-4:1997”. All the distribution lines from Chunnakam grid substations are either ELM conductor or RACOON conductor. The cable parameter of RACOON conductor and ELM conductors are summarized in table 2.1

Table 2.1: Cable parameter of RACOON and ELM conductors.

No.	Parameters	ELM	RACOON
1	Minimal Size mm^2	175	92.4
2	Number of Strands/ Strand diameter mm	19/3.76	6/4.09 1/4.09
3	Overall diameter	18.30	12.30
4	Conductor resistance (20°C) ohm/km	0.159	0.353

Source: Constructions standard for Medium voltage power distribution lines: - CEB-DCS-4:1997.

The type of the cables taken for simulation model are exactly matching with the existing electrical network. The type of the distribution lines and their actual length and the half current location details are shown in Table 2.2.

Feeder 9 further considered, Racoon conductors for feeder 12 and feeder 13.

The sag of the cables were referenced "Constructions standard for Medium voltage power distribution lines: - CEB-DCS-4:1997".

All above data were used to model the distribution line in PS-CAD Bergeron model. The distribution line pole total length (height) was taken as 11m and above ground level length was taken as 9.2m. The resistivity of the soil was taken as 100Ωm, the distance between conductors were taken as 1.05m. These details can be seen in figure 2.2.

Table 2.2: Type of the distribution lines and their actual length and the half current location.

No.	Distribution line	Cable length (km)	Half current location (km)	Cable type
1	Feeder 4	11.95	-	ELM
2	Feeder 11	14.45	-	ELM
3	Feeder 3	6.20	3.80	Racoon
4	Feeder 6	30.03	22.05	12.25km Racoon & 9.8km ELM
5	Feeder 5	5.40	4.00	Racoon
6	Feeder 2	32.80	26.00	Racoon
7	Feeder 1	24.40	12.10	Racoon
8	Feeder 7	18.10	10.80	Racoon
9	Feeder 8	11.00	7.80	Racoon
10	Feeder 9	11.80	-	Racoon
11	Feeder 10	8.80	5.20	Racoon

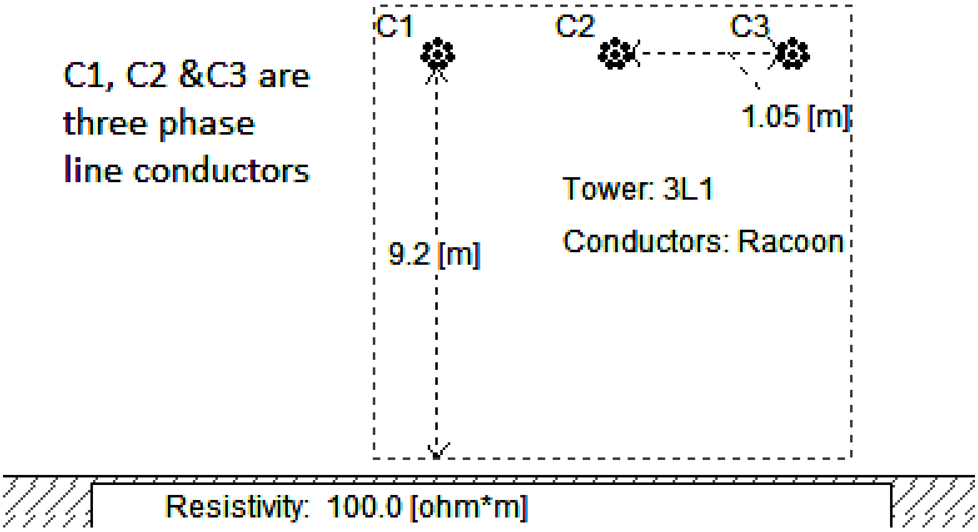


Figure 2.2 Distribution line in PS-CAD Bergeron model.

2.2.2 Transformer

The losses were mainly considered at the Transformers and the distribution lines. The transformers considered for this simulation model are at various locations such as Chunnakam Grid, Parameswara Primary, Kompayan Primary and the Ponnalai Primary substations. The losses such as copper and core losses based on the manufacture data and based on the relevant transformer capacity. The number of the transformers and their losses are shown in Table 2.3

Table 2.3: Transformers and their losses

No	Location	Capacity of Transformer (MVA)	Number of Transformers	Core loss (pu)	Copper loss (pu)
1	Chunnakam Grid Substation	31.5	2	0.000869	0.004623
2	Parameswara Primary	5.0	2	0.001320	0.010030
3	Parameswara Primary	2.0	2	0.001638	0.010650
4	Kompayan Primary	2.0	3	0.001638	0.010650
4	Ponnalai Primary	2.0	2	0.001638	0.010650

Source: LTL transformers (Pvt) Ltd.Catalog.

2.2.3 Load

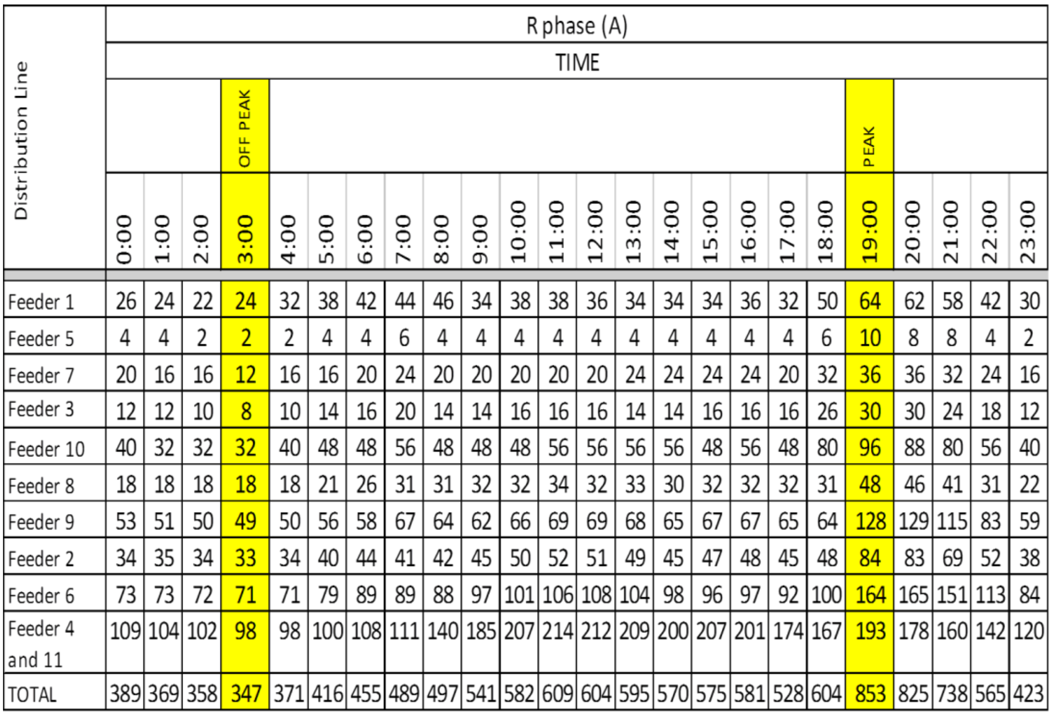
Jaffna peninsula loads are mainly depends on the house hold lighting, commercial sectors, government sectors and educational sectors. At Chunnakam power station, the load currents were measured for each and every feeder on a particular day and the corresponding peak time power factor also measured. Based on these data the loads were calculated.

It was assumed that all the phases are in balanced condition and hence the apparent power, active power and reactive power were calculated using simple electrical equations.

Apparent power = $\sqrt{3}$ * VL * IL
Active power = $\sqrt{3}$ * VL * IL * $\cos\Theta$
Reactive power = $\sqrt{3}$ * VL * IL * $\sin\Theta$

The Table 2.4 shows the reading which was taken on 5th of December 2017 at Chunnakam Grid Sub Station. The measured currents are per phase values and it is assumed that all the phases carry equal currents.

Table 2.4: Hourly taken per phase current values of distribution lines measured at Chunnakam Grid Sub Station



Distribution Line	R phase (A)																							
	TIME																							
				OFF PEAK																PEAK				
	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
Feeder 1	26	24	22	24	32	38	42	44	46	34	38	38	36	34	34	34	36	32	50	64	62	58	42	30
Feeder 5	4	4	2	2	2	4	4	6	4	4	4	4	4	4	4	4	4	4	6	10	8	8	4	2
Feeder 7	20	16	16	12	16	16	20	24	20	20	20	20	20	24	24	24	24	20	32	36	36	32	24	16
Feeder 3	12	12	10	8	10	14	16	20	14	14	16	16	16	14	14	16	16	16	26	30	30	24	18	12
Feeder 10	40	32	32	32	40	48	48	56	48	48	48	56	56	56	56	48	56	48	80	96	88	80	56	40
Feeder 8	18	18	18	18	18	21	26	31	31	32	32	34	32	33	30	32	32	32	31	48	46	41	31	22
Feeder 9	53	51	50	49	50	56	58	67	64	62	66	69	69	68	65	67	67	65	64	128	129	115	83	59
Feeder 2	34	35	34	33	34	40	44	41	42	45	50	52	51	49	45	47	48	45	48	84	83	69	52	38
Feeder 6	73	73	72	71	71	79	89	89	88	97	101	106	108	104	98	96	97	92	100	164	165	151	113	84
Feeder 4 and 11	109	104	102	98	98	100	108	111	140	185	207	214	212	209	200	207	201	174	167	193	178	160	142	120
TOTAL	389	369	358	347	371	416	455	489	497	541	582	609	604	595	570	575	581	528	604	853	825	738	565	423

Based on the above readings taken, the total per phase load currents were calculated and hence the peak and the off peak times and the corresponding load currents for each and every feeders were identified. Refer to the above the peak and the off peak load time for Jaffna peninsula were identified as below.

Jaffna Peak load Time	= 7 PM
Jaffna Off peak load Time	= 3 AM

This also can be seen in figure 2.3. That shows the hourly variation of loads for the feeders and the total load.

The power variation shown in figure. 2.3, which cause two peaks, Night peak is recorded at 7PM (major from the house hold loads) and the Day peak is mostly at 11AM (due to commercial, government and educational sectors).

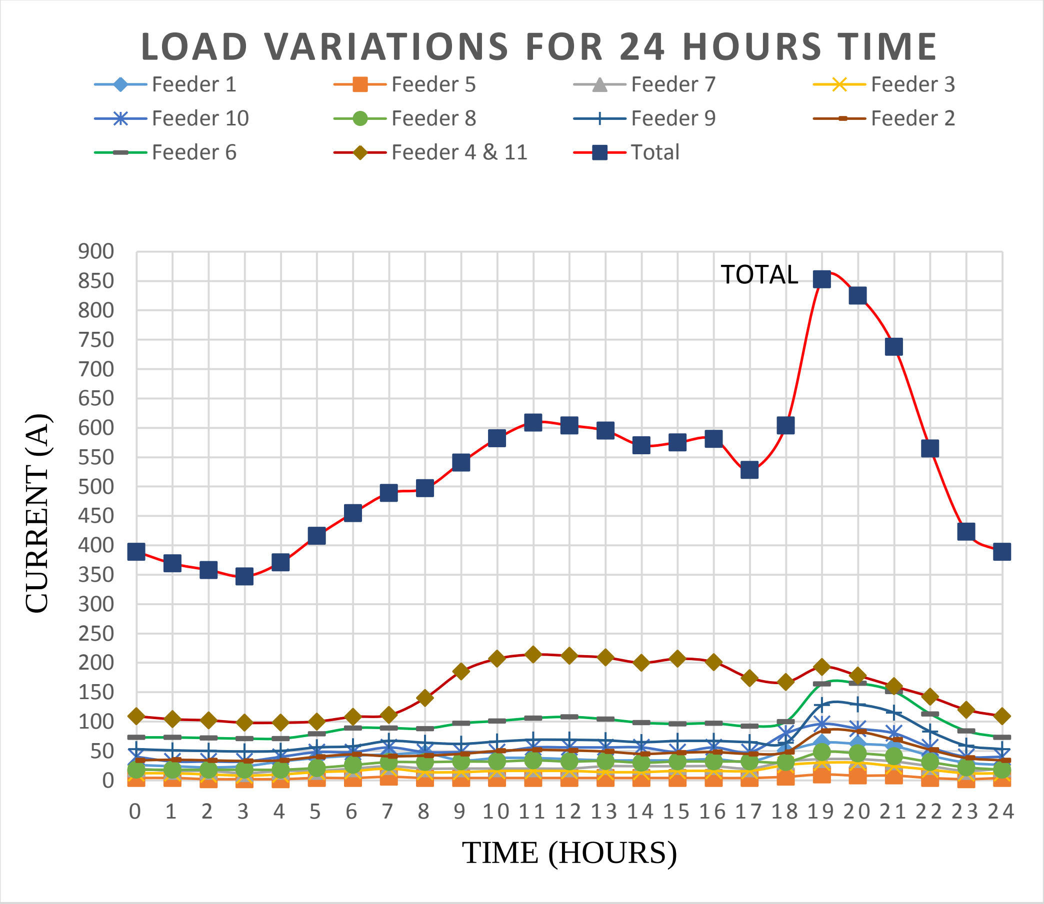


Figure 2.3 Hourly variation of loads for feeders and the total load.

Active power demand for night peak is measured as 47.089 MW and whereas the off-peak demand was 19.134 MW, same time the reactive power demand were 11.724 MVAr and 4.866 MVAr respectively. In all the outgoing feeders from the Chunnakam distribution station, the power factor was measured. At the peak loading condition, the power factor of all the feeders were recorded within the range of 0.943 to 0.998. Table 2.5 shows the power factor and the peak and off peak active and reactive power consumption of the feeders

Table 2.5: Power factor and the peak, off peak active and reactive power consumption of the feeders.

Distribution Line	OFF PEAK 'R' phase Current	PEAK 'R' phase current	Pf (Power Factor)	Apparent power (MVA)		Active power(MW)		Reactive Power (MVAr)	
				OFF PEAK	PEAK	OFF PEAK	PEAK	OFF PEAK	PEAK
Feeder 1	24	64	0.9978	1.372	3.658	1.369	3.650	0.091	0.243
Feeder 5	2	10	0.9978	0.114	0.572	0.114	0.570	0.008	0.038
Feeder 7	12	36	0.9718	0.686	2.058	0.667	2.000	0.162	0.485
Feeder 3	8	30	0.9426	0.457	1.715	0.431	1.616	0.153	0.573
Feeder 10	32	96	0.9426	1.829	5.487	1.724	5.172	0.611	1.832
Feeder 8	18	48	0.9718	1.029	2.743	1.000	2.666	0.243	0.647
Feeder 9	49	128	0.9718	2.801	7.316	2.722	7.110	0.660	1.725
Feeder 2	33	84	0.9978	1.886	4.801	1.882	4.791	0.125	0.318
Feeder 6	71	164	0.9726	4.058	9.374	3.947	9.117	0.943	2.179
Feeder 4 and 11	98	193	0.9426	5.601	11.031	5.280	10.398	1.870	3.684
TOTAL	347	853		19.833	48.754	19.134	47.089	4.866	11.724

Here the Load model used in PSCAD is three phase resistive and inductive loads whereits resistance or inductance values are calculated from the user entered rated conditions, and remains fixed throughout the simulation.

2.2.4 Simulation

The simulation was done by placing the loads at the bus bar using the values shown in table 2.5. Then the voltages at the bus bars were checked for conforming the healthy operation of the distribution system. The voltages at the models were measured by using Multimeters placed at the feeders near to the load end. These locations can be identified in figure 2.4.

The simulation network starting from the 132kV bus with the voltage source at Kilinochchi grid substation and the double circuit transmission line, which serves as a tie line that connect the Jaffna peninsula islanding power network to the national grid. PSCAD Bergeron model were used to simulate the lines because it is more suitable for voltages studies.

Figure 2.4 shows the detail model of all the components used. The lines and transformers were modeled using the parameters collected based on those line type, length, and transformer name plate information. Here appropriate line model (half current locations and the cable lengths) and transformer model are used with the available parameters. The losses are mainly considered at the distribution lines and transformers.

Here most of the cases, the simulation run time was considered as 10 seconds. This is the total length of the time that the simulation run. This is entered in seconds. If start from time zero, this is the finish time of the run.

The channel plot time is the time interval at which PSCAD plotting as well as writing data to output file.Here most of the time it is considered as 500 micro seconds.

The RMS voltages are read at the end of each distribution feeders and verified for their compliance with the standard. As per the Sri Lankan electricity Act, No. 20 of 2009, the deviation of actual voltage level from its nominal voltage shall not exceed the tolerance values ±6% but on the other hand as per the international standards this can go up to ±10%. But for this study, voltage tolerance values as ±6% is considered.

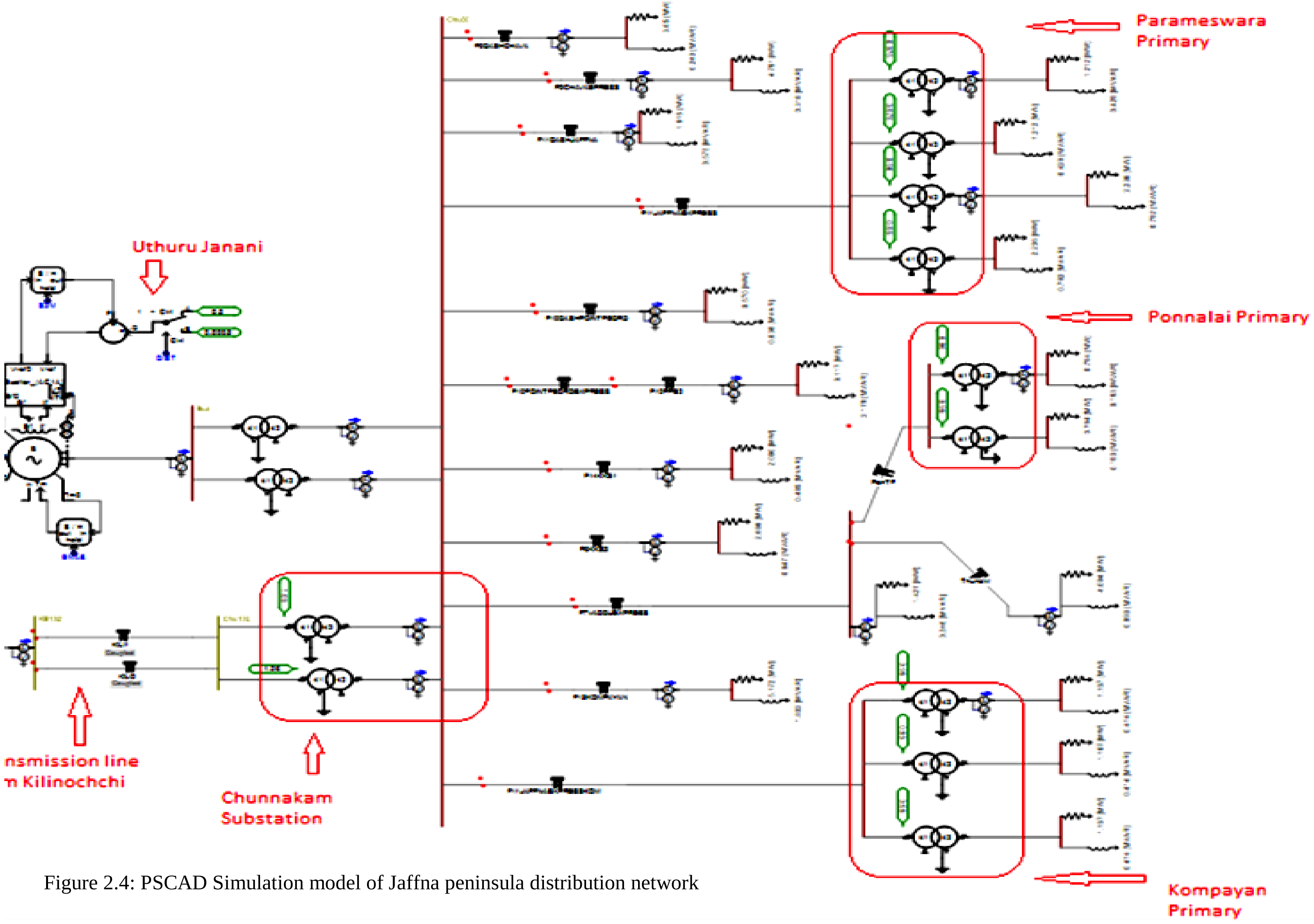


Figure 2.4: PSCAD Simulation model of Jaffna peninsula distribution network

2.2.5 Model Validation

Simulation results were recorded. The steady state line to line voltages at all feeders were checked for peak and off peak loading conditions. These results were validated with measured voltages at the selected busbars. This validated the model of the distribution network.

When the critical voltage was analyzed for peak and off peak load condition. Noticed that most of the voltages were within the acceptable voltage limit. But some feeders had under voltages. This is shown in the table 2.6.

Table 2.6: Steady state line to line voltages at the feeders for peak and off peak conditions.

Distribution Line	Steady state Voltage(pu)	
	Simulation Result	
	Peak (7PM)	Off-Peak (3AM)
CHU33Bus	0.9795	0.9927
Feeder 1	0.9645	0.9870
Feeder 5	0.9782	0.9924
Feeder 7	0.9707	0.9897
Feeder 3	0.9744	0.9913
Feeder 10	0.9632	0.9871
Feeder 8	0.9710	0.9894
Feeder 12	**0.9272**	0.9718
Feeder 2	**0.9379**	0.9762
Feeder 6	**0.9169**	0.9647
Feeder 4	**0.9373**	0.9704
Feeder 11	**0.9390**	0.9716
Feeder 13	**0.9345**	0.9750

It has been discussed that the similar observation on voltage reduction was observed in real operative condition.

3

Proposed solutions to mitigate Voltage violations in Jaffna peninsula

3.1 General methods used to solve the voltage violations

Here the solutions are proposed without any attempt of inserting any physical components of the distribution network. Only using the possible tap changers in the transformers were checked to utilized them for eliminating the under voltage problem. It was preferred to go for fixed tap changing operation rather than on-load tap changer. This is to avoid any transient.

Actually the on-load tap changers (OLTC) are used when de-energized tap changers (DETC) are not possible to overcome the voltage violations. Also the voltage violation is far below from 1pu and far above 1pu within a day of its operation. Let’s consider how to use the fixed tap operations in existing transformers.

For this

As first step: From the table 2.6, it was identified that all the voltage are always below 1pu. Fixing the tap at upper stream transformers should be considered for this case. Then the tap will be fixed with the value calculate using ‘Equation 1’. If the voltage violation is not solved then the downstream transformer tap need to be fixed based on the similar method as in ‘Equation 1’. Basically this calculation of the tap and keep it as its fixed tap position, shifts the transformer’s operation around the 1pu of its output voltage.

$$Tap_{\max} = \frac{V_{\max\_Off\_Peak}}{1+\left(\frac{V_{\max\_Off\_Peak} - V_{\min\_Peak}}{2}\right)}$$

$$Tap_{\min} = \frac{V_{\min\_Peak}}{1-\left(\frac{V_{\max\_Off\_Peak} - V_{\min\_Peak}}{2}\right)}$$

$$Tap = \frac{Tap_{\max} + Tap_{\min}}{2} \qquad \text{---------}(1)$$

Second step: If the fixed tap method is not worked then on-load tap changer operation can be designed base on similar method on upstream to downstream transformers. This is further discussed in 3.2.

Third step: If the voltage variation is too fast or fluctuating components is observed, which is expected with increasing penetration on renewable energy generation technologies, then the fast acting varying compensation devices such as STATCOM / SVC can be studied for solutions. This is further discussed in 3.3.

3.1.1 Proposed solutions to the Jaffna peninsula distribution system using De-Energized tap changer (DETC)

It can be seen from the study result from Table 2.6 that all the voltages are below 1pu. Therefore the upper stream transformer fix taping point is calculated based on the Equation 1. From the Table 2.6, the maximum voltage during off peak loading condition Vmax_Off_Peak = 0.9927pu and minimum voltage during peak loading condition Vmin_Peak = 0.9169pu. As a result the fixed tap position to be set is 0.95.

This was set in the simulation to the tap of the upper stream transformer, which is the incoming feeder to the Jaffna Peninsula. The simulation results of voltages at the busbars were measured again and the recorded results are shown in Table 3.1.

This shows all the busbars are with very good healthy voltages. The proposed method and solution is validated through this simulation results.

Table 3.1: Steady state line to line voltages at the feeders for peak and off peak conditions when Chunnakam Grid Sub Station upper stream transformer fixed tap value 0.95.

Distribution Line	Steady state Voltage(pu)	
	Simulation Result	
	Peak (7PM)	Off-Peak (3AM)
CHU33Bus	1.0042	1.0180
Feeder 1	0.9888	1.0122
Feeder 5	1.0028	1.0178
Feeder 7	0.9952	1.0150
Feeder 3	0.9989	1.0166
Feeder 10	0.9875	1.0123
Feeder 8	0.9955	1.0147
Feeder 12	0.9506	0.9966
Feeder 2	0.9616	1.0011
Feeder 6	0.9400	0.9894
Feeder 4	0.9609	0.9951
Feeder 11	0.9627	0.9965
Feeder 13	0.9581	0.9999

3.1.2 Possible solutions which can be applied for future demand growth

Still have not utilize the maximum usage of the above method in the distribution network. For example the DETC can also be set for primary transformers. From Table 3.1, 'Feeder 4' Vmax_Off_Peak = 0.9951pu, Vmin_Peak = 0.9609pu, 'Feeder 11' Vmax_Off_Peak = 0.9965pu and Vmin_Peak = 0.9627. From these values and using 'equation 1', it can be calculated to set all Pameswara and Kompayan transformers taps to 0.975. This can further improve the voltages at feeder 4 and feeder 11, when the customer demand increases in future.

But the case of ‘Feeder 6’ it have no primary transformers to go for DETC, but one of its line segment which is 12.25km Racoon conductor can be replaced by ELM. For ‘Feeder 9’ Ponnalai transformers can go for DETC but that will not improve the voltages at ‘Feeder 13’. Therefore can go for ELM conductor for ‘feeder 9’. To improve ‘Feeder ‘2 can replace Racoon to ELM cable type. After doing all these, the simulation updated voltages recorded are shown in Table3.2. This results shows very healthy operational conditions, which can also handle future demand growth up to some more extend.

Table 3.2: Steady state line to line voltages at the feeders for peak and off peak conditions when apply more possible solutions.

Distribution Line	Steady state Voltage(pu)			
	Simulation Result			
	Peak (7PM)		Off-Peak (3AM)	
	Before	After	Before	After
CHU33Bus	0.9795	1.0037	0.9927	1.0178
Feeder 1	0.9645	0.9884	0.9870	1.0120
Feeder 5	0.9782	1.0024	0.9924	1.0176
Feeder 7	0.9707	0.9947	0.9897	1.0148
Feeder 3	0.9744	0.9985	0.9913	1.0164
Feeder 10	0.9632	0.9870	0.9871	1.0122
Feeder 8	0.9710	0.9950	0.9894	1.0145
Feeder 12	**0.9272**	0.9656	0.9718	1.0027
Feeder 2	**0.9379**	0.9829	0.9762	1.0098
Feeder 6	**0.9169**	0.9595	0.9647	0.9984
Feeder 4	**0.9373**	0.9838	0.9704	1.0198
Feeder 11	**0.9390**	0.9861	0.9716	1.0214
Feeder 13	**0.9345**	0.9732	0.9750	1.0060

3.2 Usage of on load tap changer (OLTC) for Distribution system network

3.2.1 Usage of on load tap changer (OLTC) for Jaffna Distribution system network

As discussed in 3.1, If the voltage violation cannot be resolved using DETC then only need to go for the next method which is using on-load tap changer (OLTC) operation. This method also can be designed from upstream to downstream transformers.

Here the Jaffna Distribution Network was studied with the lowest fixed tap position for off peak and peak load operating conditions. Analysis was done to check the method for removing the voltage violations. In other words at the lowest tap position, any under voltage violation occurred during the peak loading condition then OLTC is not suitable for this network or at the lowest tap position if any over voltage occurred during the off peak loading condition then OLTC have possibility to remove this voltage violation.

As the Jaffna Distribution Network voltage violations for the present load can be resolved by using DETC, the study also was continued for future increased load to check the viability of On Load Tap Changer (OLTC) operations for a Jaffna Distribution Network.

This was done by increase the present peak load at each and every feeders by a percentage of load addition. That is the addition of 60% to 25% of present peak load. Table 3.3 shows the variation of voltages pattern. First of all, the upper stream transformer DETC tap position was set to its minimum value of 0.9 and then the loads were varied as stated above (results are shown in first five columns). Further the simulation was carried out with a light load (shown in the last column).

It can be noticed that up to 125% of the peak load, the DETC method can be used to manage the network without violating the voltage limits. During the light load operation, voltages were within the limits.

However, when the load increases above 125% of the peak load, under voltages were observed in some feeders. It has to be noted that the tap positions are already at their lowest values. Therefore the OLTC will not be an option for the Jaffna peninsula distribution network when the loads are increased above 125% of their existing values.

Table 3.3: Steady state line to line voltages at the feeders with tap value of 0.9 and up to 160% of the peak load conditions.

Distribution Line	Steady state Voltage(pu)					
	Simulation Result					
	VOLTAGE with 160% of PEAK load at 0.90Tap	VOLTAGE with 150% of PEAK load at 0.90Tap	VOLTAGE with 140% of PEAK load at 0.90Tap	VOLTAGE with 130% of PEAK load at 0.90Tap	VOLTAGE with 125% of PEAK load at 0.90Tap	Light load with 0.9Tap
CHU33Bus	1.0144	1.0171	1.0198	1.0225	1.0238	1.0541
Feeder 1	0.9895	0.9938	0.9980	1.0021	1.0042	1.0540
Feeder 5	1.0121	1.0150	1.0178	1.0207	1.0221	1.0541
Feeder 7	0.9998	1.0034	1.0070	1.0106	1.0123	1.0541
Feeder 3	1.0059	1.0091	1.0123	1.0155	1.0171	1.0540
Feeder 10	0.9876	0.9919	0.9962	1.0005	1.0026	1.0539
Feeder 8	1.0003	1.0039	1.0074	1.0110	1.0127	1.0540
Feeder 12	0.9292	0.9369	0.9445	0.9522	0.9560	1.0530
Feeder 2	0.9461	0.9528	0.9595	0.9663	0.9697	1.0541
Feeder 6	0.9130	0.9214	0.9299	0.9384	0.9427	1.0537
Feeder 4	0.9452	0.9520	0.9588	0.9656	0.9690	1.0522
Feeder 11	0.9475	0.9542	0.9609	0.9677	0.9710	1.0529
Feeder 13	0.9412	0.9481	0.9550	0.9620	0.9655	1.0537

Here it can be noticed that up to 125% of the peak load, can be managed with DETC. Even at light load, voltages do not deviate from standard. Therefore it is not necessary to go for OLTC at Jaffna distribution network.

3.2.2 Common problems with OLTC

Further, OLTC switching operation causes voltage transient/sag. This is due to the arcing at the OLTC switches, which also causes contact erosion and carbonization of the arcing switch oil. As a result the maintenance cost and time will be increased.

This issue can be further discuss using the tap changing operation of a Resistor oil type OLTC. Here Figure 3.1 shows the switching sequence of the tap selector and Figure 3.2 shows the switching sequence of the diverter switch.

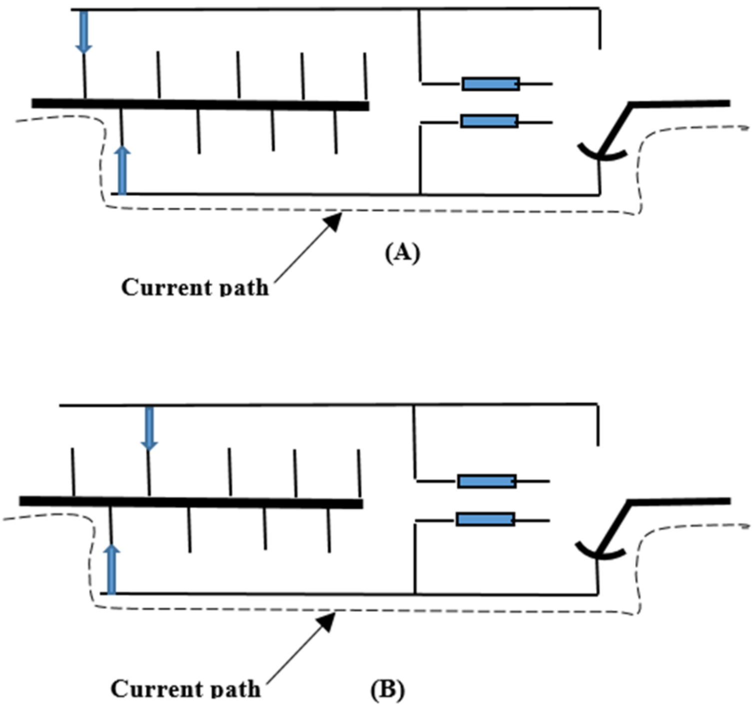


Figure 3.1 Switching sequence of the OLTC tap selector.

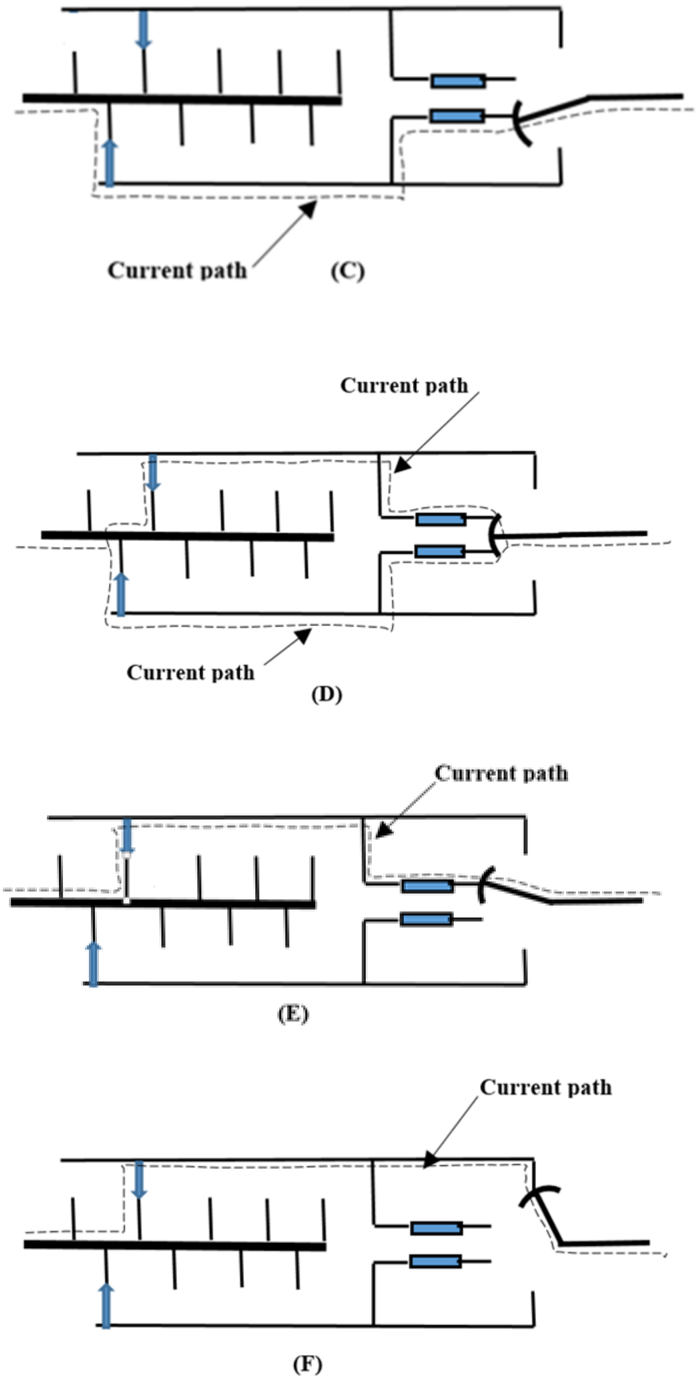


Figure 3.2 Switching sequence of the OLTC diverter switch.

During the tap changing operation the ‘next tap’ is first preselected by the tap selector at no load. After that the diverter switch transfers the load current from the tap in operation to the preselected tap. Figures 3.1 and 3.2 shows this changes.

The switching time of a diverter switch is in between 40 and 60 milliseconds with today’s designs. Here the transition resistors are loaded for 20–30 milliseconds, The total operation time of an OLTC is in between 3 and 10 seconds, depending on the respective design. This causes voltage sag. Further, the arcing at the diverter switch causes contact erosion and carbonization of the arcing switch oil, which need careful and high maintenance.

3.2.3 Usage of on load tap changer (OLTC) for a simple distribution network

As the Jaffna Distribution System Network is not suitable to study the viability of the OLTC operation to mitigate voltage violations a simple network was modelled to study the OLTC operations.

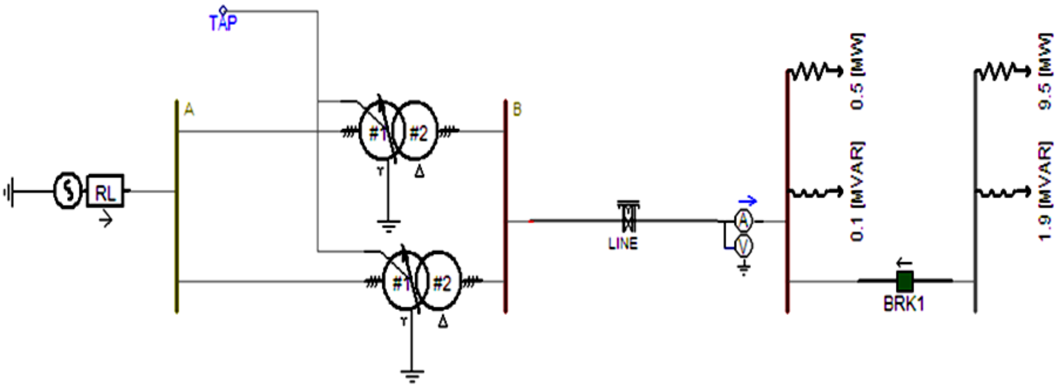


Figure 3.3 A simple network was modelled to study the OLTC operations.

Figure 3.3 shows a simple network which was developed in PSCAD to study the method of OLTC to resolve the voltage violations.

Further a control system was developed to operate the OLTC to achieve the best customized operation to effectively use the OLTC to avoid voltage violation. This can be seen in figure 3.4.

Here a 30km Racoon conductor is connected to a light load and then a heavy load is engaged by BRK1 switching operation. The steady state voltage at the load terminal was measured in this study. BRK1 switch operation was arranged in such a way that initially open, closed at 0.7s and again open at 1.0s. During this period the load terminal voltage varies in from 0.8836 to 0.9939. This shows that the voltage goes out of its lower limit. Hence to mitigate this violation, the transformer DETC position were set to 0.93 and again the load voltage was observed, which varies from 0.9500 to 1.0687. This shows that the voltage exceeds its upper limit. In such situation, the DETC cannot be used to solve this problem. Therefore the next option is to go for OLTC.

In this study during the light load condition the DETC position was set to 0.99 and found that no violation of voltages and it was within the upper limit. Therefore a solution was identified to set the primary side of 2x35.5MVA 132/33 step down transformer TAP at 0.93 or 0.99 when the voltages reached to their lower limit and upper limit respectively. In other words this will help to operate without violating the voltage limits during light and heavy load operating conditions. This is only possible through the OLTC.

Further to the above as the OLTC operation needs an automatic control. The situation was carefully studied and an appropriate control system was developed. The idea of this controller is based on hysteresis control operation, which eliminates the malfunctioning in the switching operation of the OLTC. Hence a quality solution is achieved.

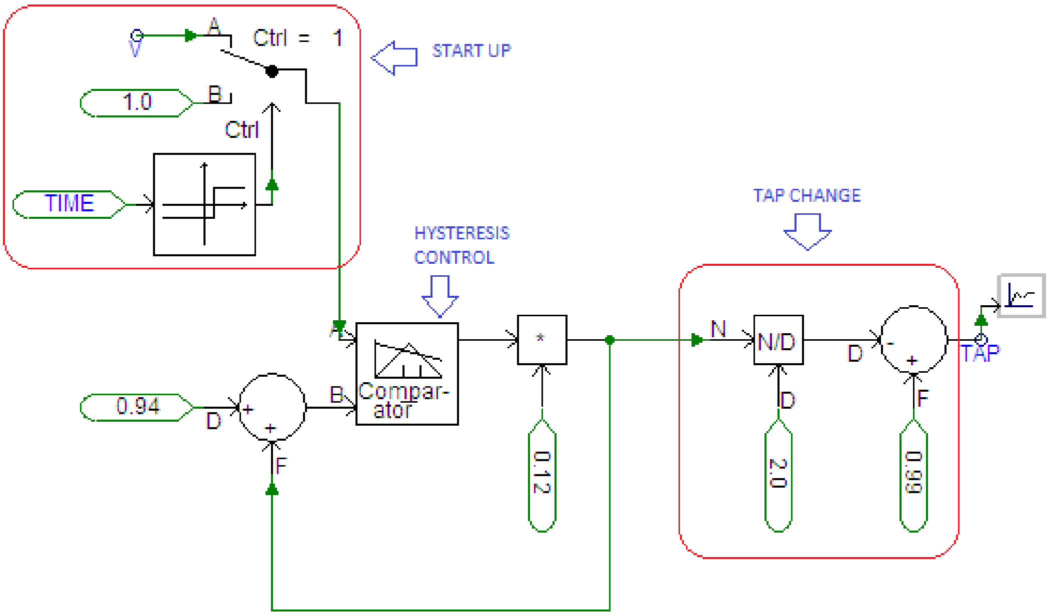


Figure 3.4 A control system which was developed to operate the OLTC.

The startup block is added to avoid the unnecessary operations in the simulation only. In practice this startup section used to energize the controller after its measurements section gets stabilized.

The operation of hysteresis control block is designed in such a way that when the comparator ‘A’ input greater than ‘B’ input, the output of the comparator will be ‘0’. On the other hand when the comparator ‘A’ input less than ‘B’ input, the output of the comparator will be ‘1’. This helps to shift the value of the comparator input B from 0.94 (lower voltage limit) and 1.06 (upper voltage limit). The shifting of the threshold value, at the comparator input B, helps to avoid malfunction due to variation in the measured voltage due to the change of the OLTC tap positions. This is the excellent operation of adding the hysteresis control block in this control technique.

The operation of the Tap change block is to change the TAP position from 0.99 to 0.93 according to the calculated control values.

Figure 3.5 shows the variation of terminal voltage and the TAP setting against time. It can be noticed that the TAP value changed from 0.99 to 0.93 when the terminal voltage intend to decrease below 0.94 and again increased back to 0.99 when the terminal voltage intend to increase above 1.06pu. The simulation result is conforming that the voltage is kept within its limits by the OLTC operation using the proposed automatic and customized control technique.

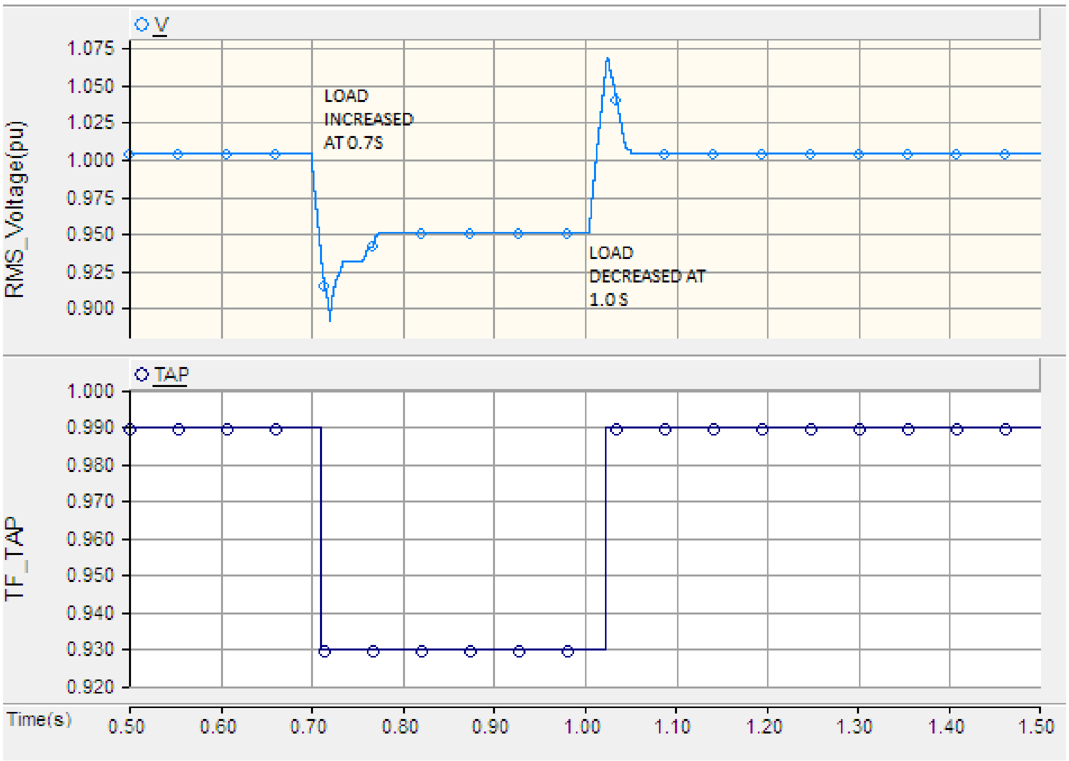


Figure 3.5 Variation of terminal voltage and the TAP setting against time

3.3 Study the viability of STATCOM for solving problems in a distribution system network

As discussed in 3.1, if the voltage variation is too fast or fluctuating components is observed, then the fast acting varying compensation devices such as STATCOM / SVC can be studied for solutions.

However from literatures, it is realized that the STATCOM is more economical only when it is required for eliminating fast variations in the voltage. This study was done as it will be required in the future. Because Sri Lanka has huge potential for electricity generation from the renewable energy technologies. The electricity generation using the renewable energy technologies also introduces fast varying fluctuations in its generations. Therefore by considering the future development of Sri Lanka’s potential renewable energy technology, the STATCOM applications will be required. This created an opportunity to study the STATCOM in details.

Referred to 3.2, voltage sag created by the switching operation of an OLTC is one of the practical problem that need to be resolved. This type of fast variation in voltage causes malfunctions of the sensitive loads in the distribution network and it can be mitigated by using STATCOM.

Further this Chapter fully focus on the STATCOM control and its integrated applications together with the OLTC. Here (i) The STATCOM detail model using IGBT switches, (ii) A small scale distribution network, (iii) OLTC control, (iv) Converter control, (v) AC terminal voltage droop control and (vi) DC link voltage regulatory control were designed to operate to solve the voltage variations.

Other than that a Phase Locked Loop (PLL) is developed to identify the phase angle and Park Transformation is used to identify the phase error. According to the STATCOM system control, its internal voltage was developed. The STATCOM converter control used the sine-triangular Pulse Width Modulation (PWM), to generate the gate pulses.

3.3.1 Park Transformation

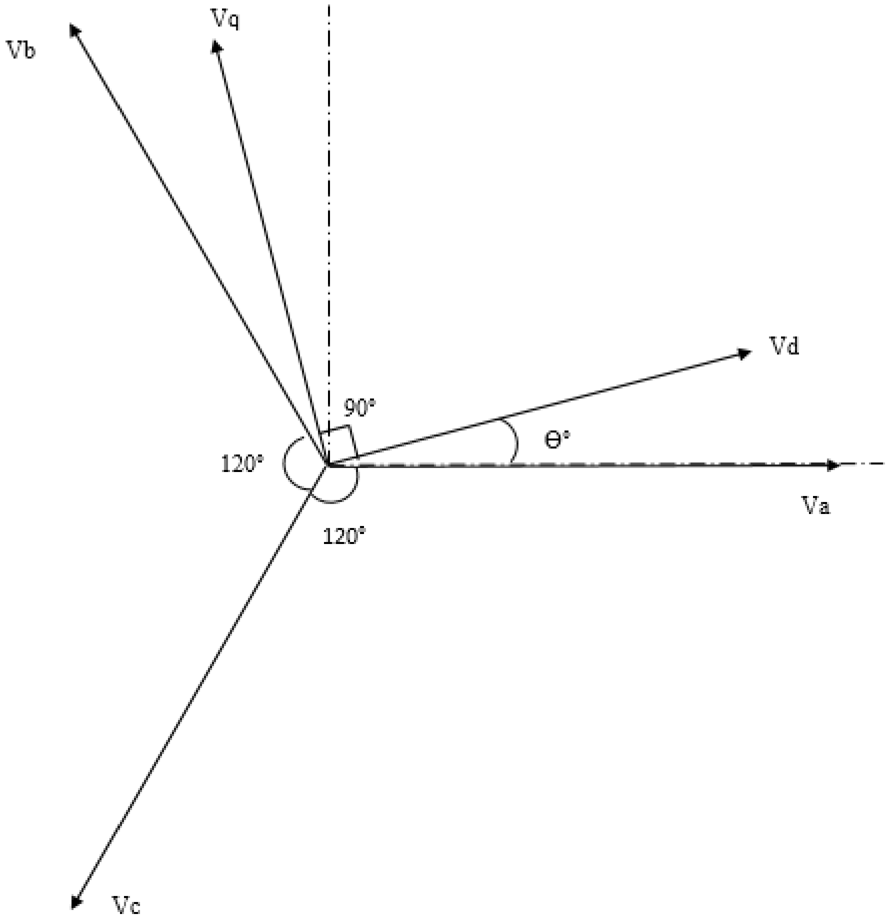


Figure 3.6 Vd and the Vq components of Park transformation

Here the Va, Vb and Vc are three phase instantaneous voltages.

$$Va = Vm\cos\Theta$$

$$Vb = Vm\cos(\Theta - 120)$$

$$Vc = Vm\cos(\Theta - 240)$$

Vd, Vq are d and q axis park transformation voltage components. This is shown in figure 3.6.

Then, Vd, Vq can be written as below.

$$Vd = Va\cos(\Theta) + Vb\cos(120 - \Theta) + Vc\cos(120 + \Theta)$$

$$Vq = -Va\sin(\Theta) + Vb\sin(120 - \Theta) - Vc\sin(120 + \Theta)$$

When the system is balanced and steady using the above equations the values for Vd and Vq can be simplified as below using simple trigonometric equations.

$$Vd = \frac{3}{2}\,Vm$$

$$Vq = 0$$

But when there is a phase error it can be identified from the value of Vq.

3.3.2 Phase Lock Loop (PLL)

As discussed earlier, the PLL is used to identify the phase angle. Figure 3.7 shows the PLL model. The input ‘Vq’ is the ‘q’ axis component of the park transformation. And the output ‘Theta2’ varies in between ‘0’ to ‘360’ degrees. Normally frequency is 50Hz, if any variation occurs then frequency change as per the output value of the PI controller. Here an integrator and a comparator are combined to produce the ‘Theta2’ output. When the comparator input value ‘A’ greater than ‘360’ degrees, then the comparator output value become ’1’ and it will reset the integrator output value that is ‘Theta2’ to ‘Zero’. On the other hand when the comparator input value ‘A’ less than ‘360’ degrees, then the comparator output value become ’0’ and it will not reset the integrator output value.

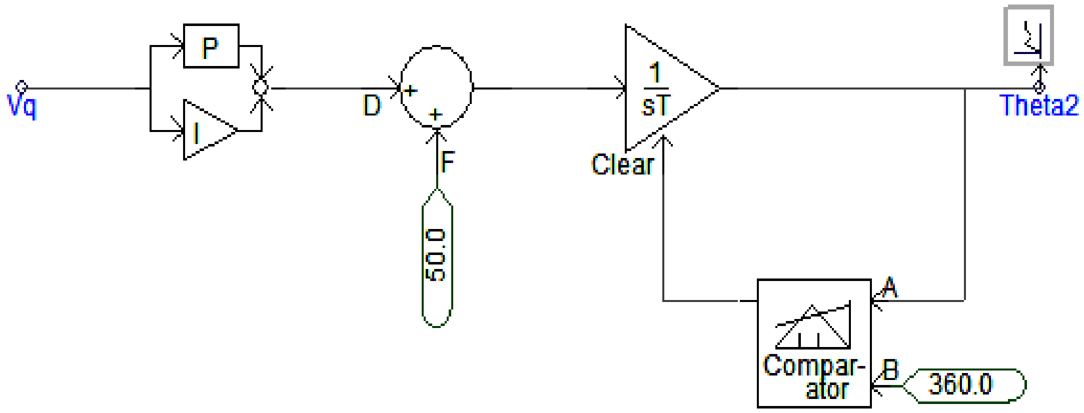


Figure 3.7 Phase Lock Loop (PLL) model.

As a result, the value of ‘Theta2’ vary in between ‘0’ to ‘360’ degrees. The PSCAD output value of ‘Theta2’ variation is shown in figure 3.8.

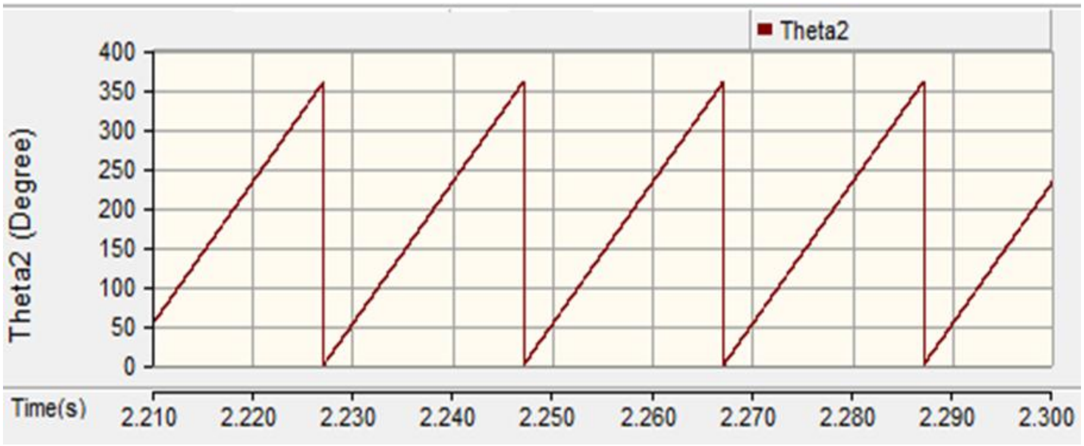


Figure 3.8 Variation of PLL output value ‘Theta2’

The input value ‘Vq’ for the PLL can be derived from the basic idea of ‘Park Transformation’ ‘q’ axis component. The PSCAD model of this is shown in figure 3.9. Here Vna, Vnb and Vnc are the three phase instantaneous voltages measured at the distribution network which is in per unit (pu). Then the control output voltages Va2, Vb2 and Vc2 are used to derive Vq voltage.

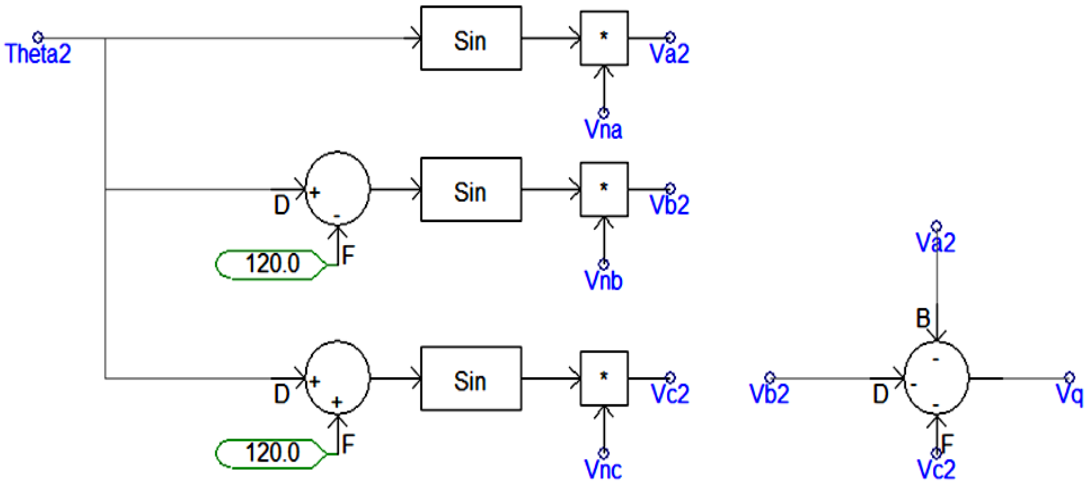


Figure 3.9 Derivation of Vq, Park transformation ‘q’ axis component.

3.3.3 A simplified network used to study the STATCOM performance of mitigating voltage violations

A simple network was developed in PSCAD to study the performance of STATCOM and its mitigation of voltage violations. Figure 3.10 shows the network arrangement. Here a 30km Racoon conductor is connected to a light load and then a heavy load is engaged by breaker (BRK1) switching operation. The steady stage voltage at the load terminal was measured in this study. BRK1 switch operation was arranged in such a way that initially open, then closed at 2s.

When BRK1 closed after 2 seconds that introduce a step increase in the load. When load increase, the OLTC operate to increase the voltage. However, the OLTC operation was not enough to boost the voltage drop and also it introduces a voltage sag too. This was eliminated by using STATCOM in this study.

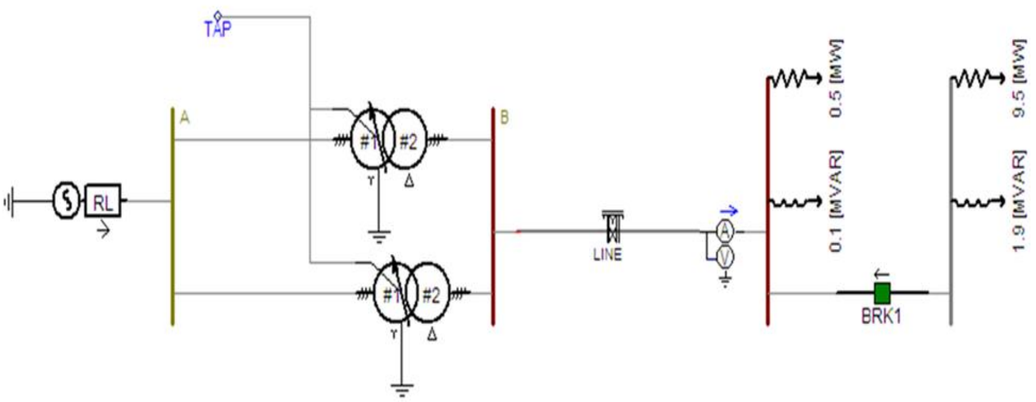


Figure 3.10 A simple network used to study the performance of STATCOM.

3.3.4 STATCOM Power Electronic Circuit

A STATCOM detail model was studied with using IGBT switches which provide the fast switching capability for the control of Converter control block. Figure 3.11 shows the STATCOM power Electronic Circuit that consists of IGBT control converter, two number of DC-Link capacitors each 250mF, DC batteries which uses for the capacitor initial charging and disconnected after 0.5 seconds. This is achieved by BRK2 and BRK3 switching operation. That is BRK2 and BRK3 are initially CLOSED and OPEN after 0.5 second.

This is a 6 pulse STATCOM where 6 IGBTs are triggered by respective G1 to G6 pulses. Here Vcdc is the DC-Link voltage measured across the capacitors where the both capacitor connection point is earthed. The batteries are connected in such a way when the BRK2 and BRK3 are closed the DC-Link voltage Vcdc can be applied across the batteries.

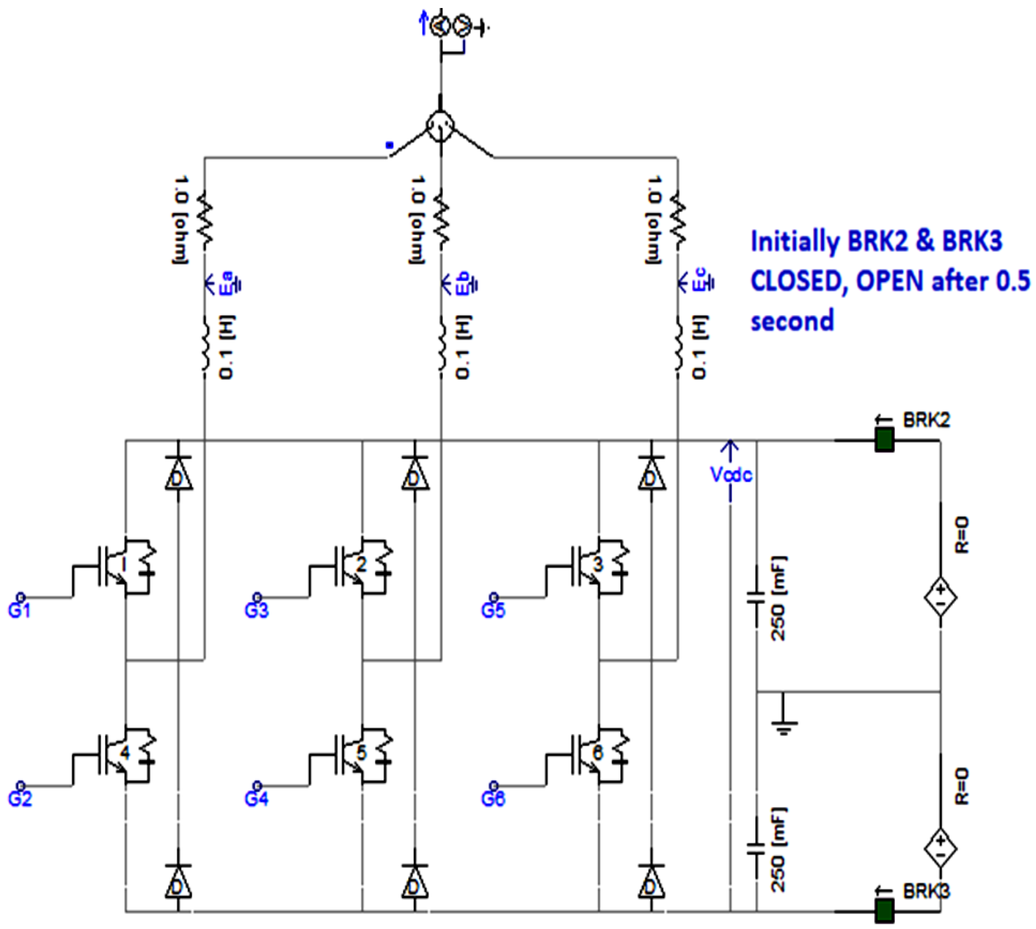


Figure 3.11 STATCOM power electronic circuit.

3.3.5 System Control – AC terminal Voltage Droop Control

STATCOM is a shunt connected device. When the distribution line system voltage is low, STATCOM inject reactive power to the system and increase the system voltage. On the other hand when the system voltage is high, STATCOM absorb reactive power and hence the system voltage decreases.

Here the ‘AC terminal voltage droop control’ define the system reference voltage (Vref). It vary in between an upper (Vmax) and a lower (Vmin) limits. As per the Sri Lankan electricity Act, No. 20 of 2009, the deviation of actual voltage level from its nominal voltage shall not exceed the tolerance values ±6%. Therefore here the Vmax RMS voltage was taken as 1.06pu and Vmin RMS voltage was taken as 0.94pu. Figure 3.12 shows that how the Vref varies in between Vmax and Vmin.

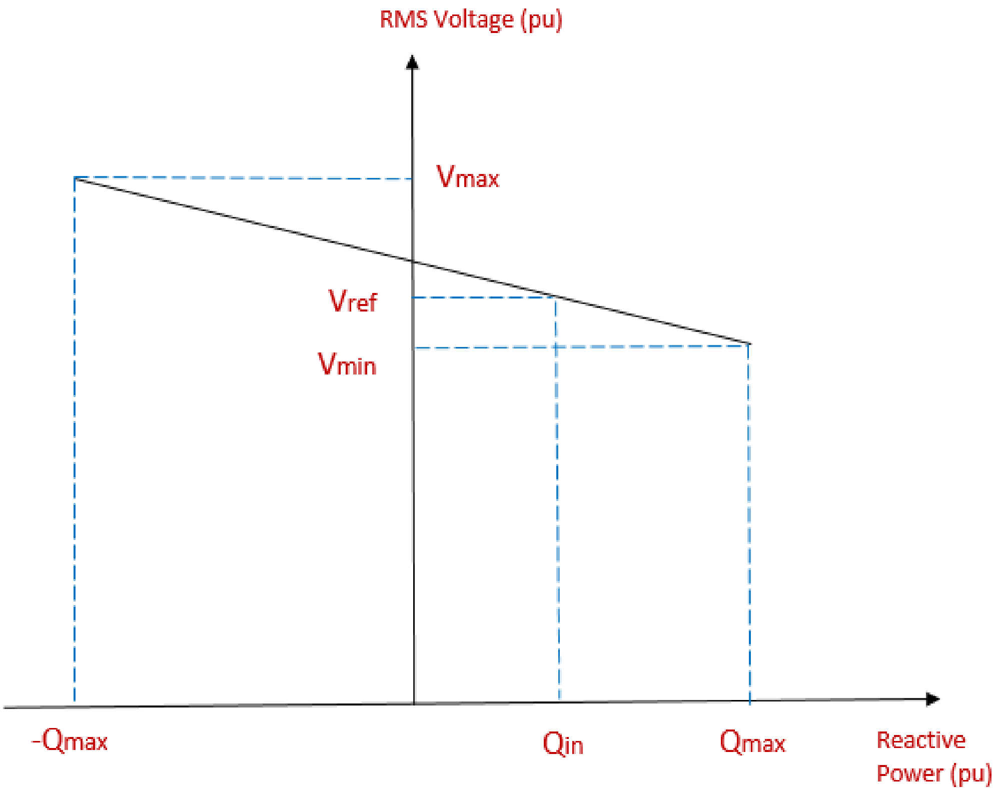


Figure 3.12 Variation of system reference voltage Vref in between Vmax and Vmin.

When the system voltage is near to Vmin STATCOM inject Qmax in to the distribution line system. On the other hand when the system voltage is near to Vmax STATCOM absorb Qmax from the distribution line system

From figure 3.12 using similar triangle the below equations can be derived.

$$\frac{\left(\frac{V_{\max}+V_{\min}}{2}\right)-V_{\min}}{Q_{\max}}=\frac{\left(\frac{V_{\max}+V_{\min}}{2}\right)-V_{ref}}{Q_{in}} \quad \text{-------}(2)$$

This can be further simplified by replacing Vmax with 1.06 and Vmin with 0.94. Hence the equation can be further simplified to the below form.

$$V_{ref} = 1 - 0.06 \left(\frac{Q_{in}}{Q_{\max}} \right) \qquad \text{- - - - - - - - (3)}$$

Based on the above equation (3) the AC terminal voltage droop control can be designed. It is shown in below figure 3.13.

Here the ‘Qstat’ is the reactive power injected from the STATCOM to the distribution line system. That is the ‘Qin’ when applied in the above equation (3). From figure 3.10, the value of heavy load reactive power is 2MVAr. Hence the Q_{max} value was taken as 3MVAr. This can vary depending on the distribution network. Here a limiter is used to control the upper and the lower limit of Vref to keep within1.06 and 0.94 pu respectively. Here 0.06 which is a constant used as per equation (3).

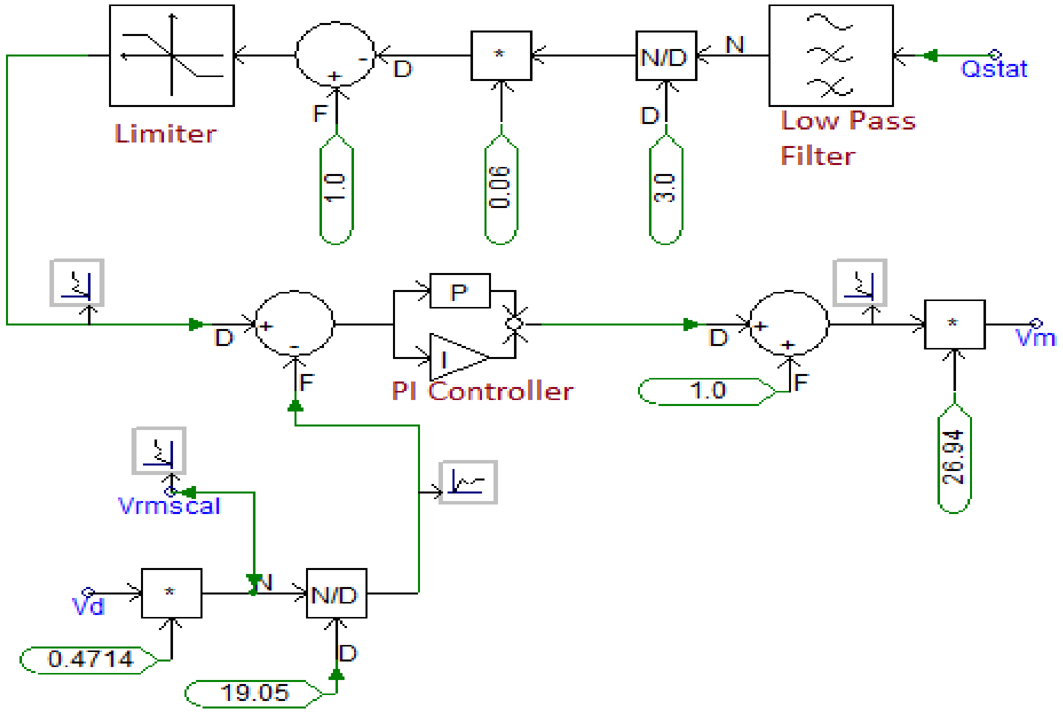


Figure 3.13 AC terminal voltage droop control.

The distribution line instantaneous voltage Vrms can be represented as 0.4714 Vd. This can be derived from the below equation (4).

$$Vrms = \frac{\mathrm{Vm}}{\sqrt{2}} = \frac{\sqrt{2}}{3}Vd = 0.4714Vd \qquad \text{- - - - - - - - - - -} (4)$$

Here ‘Vm’ is the peak value of the STATCOM generated AC voltage. That is why, for a 33kV distribution system a constant value 26.94 is used to derive the value of ‘Vm’.

Further a constant 19.05 is used, because for a 33kV line to line voltage distribution system the RMS value of the line to neutral voltage is 19.05. This value used for pu conversion.
Figure 3.14 shows that how ‘Vd’ is derived.

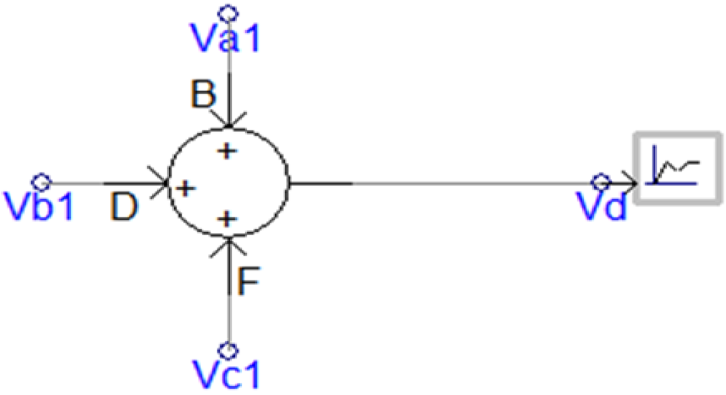


Figure 3.14 Derivation of Vd, Park transformation ‘d’ axis component.

‘Vd’ is derived from Va1, Vb1 and Vc1.

Figure 3.15 shows how Va1, Vb1 and Vc1 are derived.

Here Va, Vb and Vc are STATCOM internal voltages. This is used for the converter control of the STATCOM, will be discussed under Converter Control.

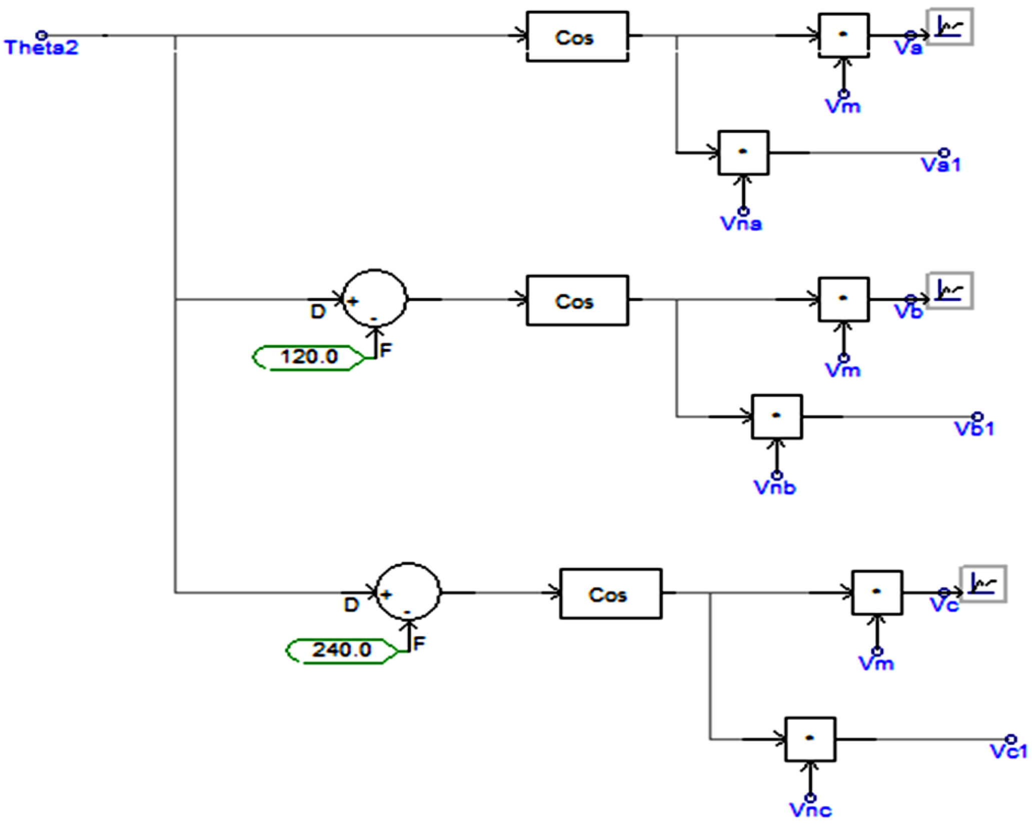


Figure 3.15 Derivation of Vd, from theta2.

3.3.6 STATCOM DC Link Voltage Regulatory control

STATCOM DC-Link side have capacitors. The magnitude of the capacitor is chosen in such a way that the DC voltage across its terminals remain fairly constant during the entire operation. Here DC-Link voltage Vcdc was controlled by using a variable ‘Delta’ measured in ‘degrees’. The control of Vcdc was done through the regulatory control of the STATCOM. This control model is shown in figure 3.16.

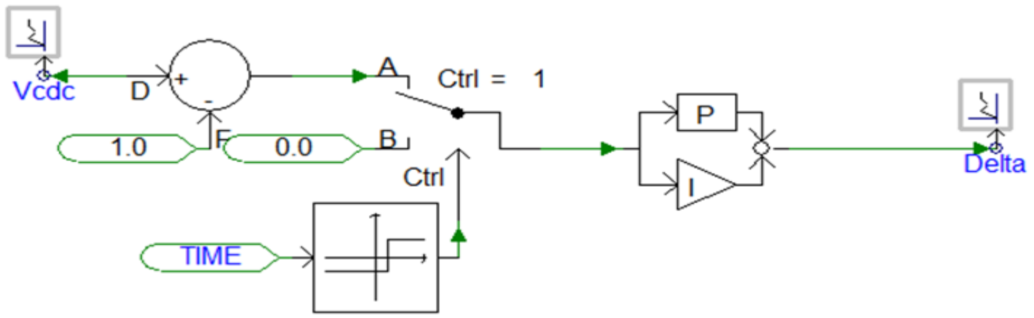


Figure 3.16 STATCOM DC-Link voltage regulatory control.

Here the ‘Vcdc’ was used to control the value of ‘Delta’. This was done by adding ‘Delta’ with ‘Theta2’ to produce Va, Vb, Vc, Va1, Vb1 and Vc1. This control model is shown in figure 3.17.

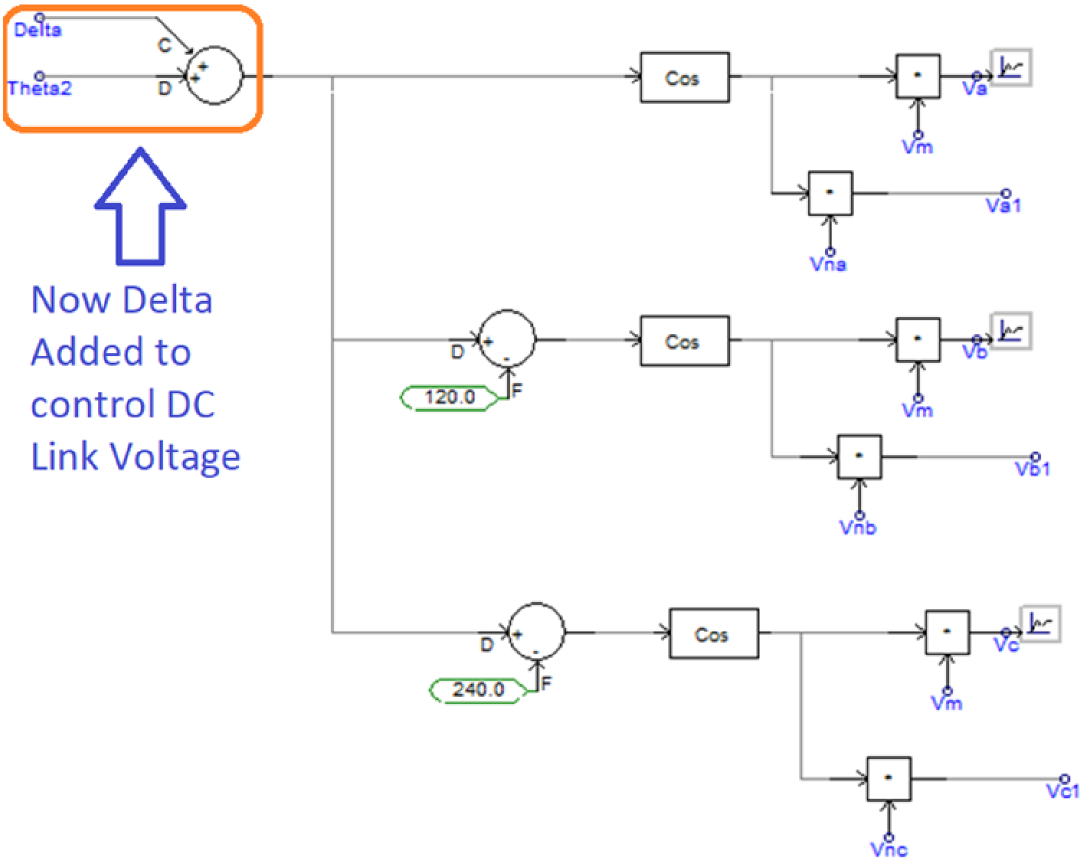

Now Delta Added to control DC Link Voltage

Figure 3.17 Control model of DC-link voltage.

3.3.7 Converter Control using Sine-Triangular PWM

Converter control is used to operate the IGBT switches which connect the DC input circuit directly to the AC output circuit. G1 to G6 are the pulses that switch the six number of IGBTs respectively. There are three numbers of comparators that are used to generate these pulses. This is shown in below figure 3.18. A 3000Hz high frequency triangular wave is fed to the 'B' input of the comparator. All three comparators receive the same wave simultaneously. On the other hand the 'A' input of the comparators fed with STATCOM internally generated voltages Va, Vb and Vc. When Va greater than 'Vtri' comparator output G1 value become '1'. Similarly when Va less than 'Vtri' comparator output G1 value become '0'. Here the output '1' will 'ON' the IGBT and output '0' will 'OFF' the IGBT. This is shown in figure 3.19.

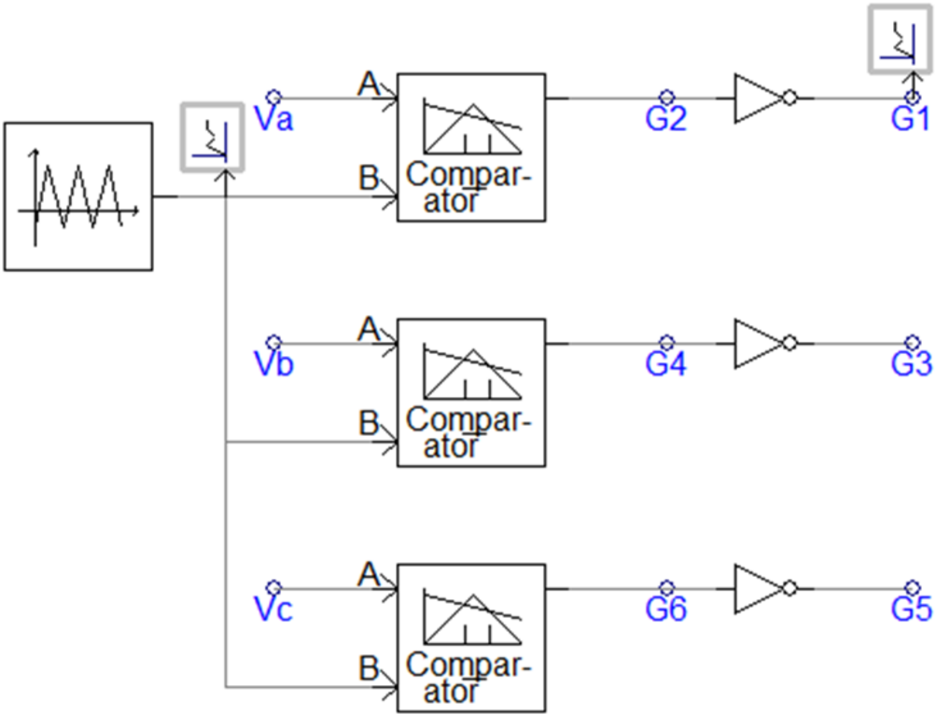


Figure 3.18 Converter Control using Sine-Triangular PWM

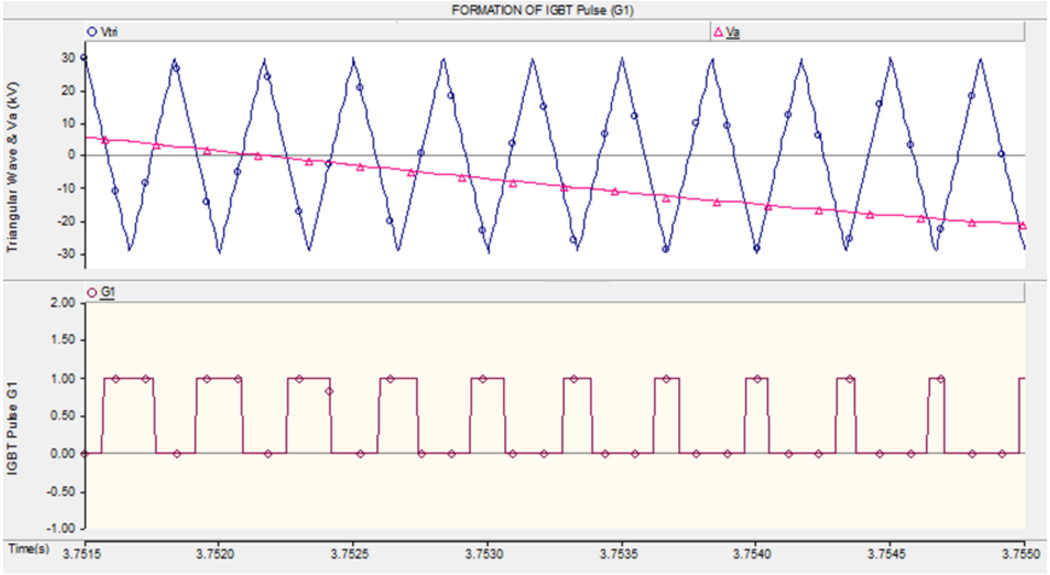
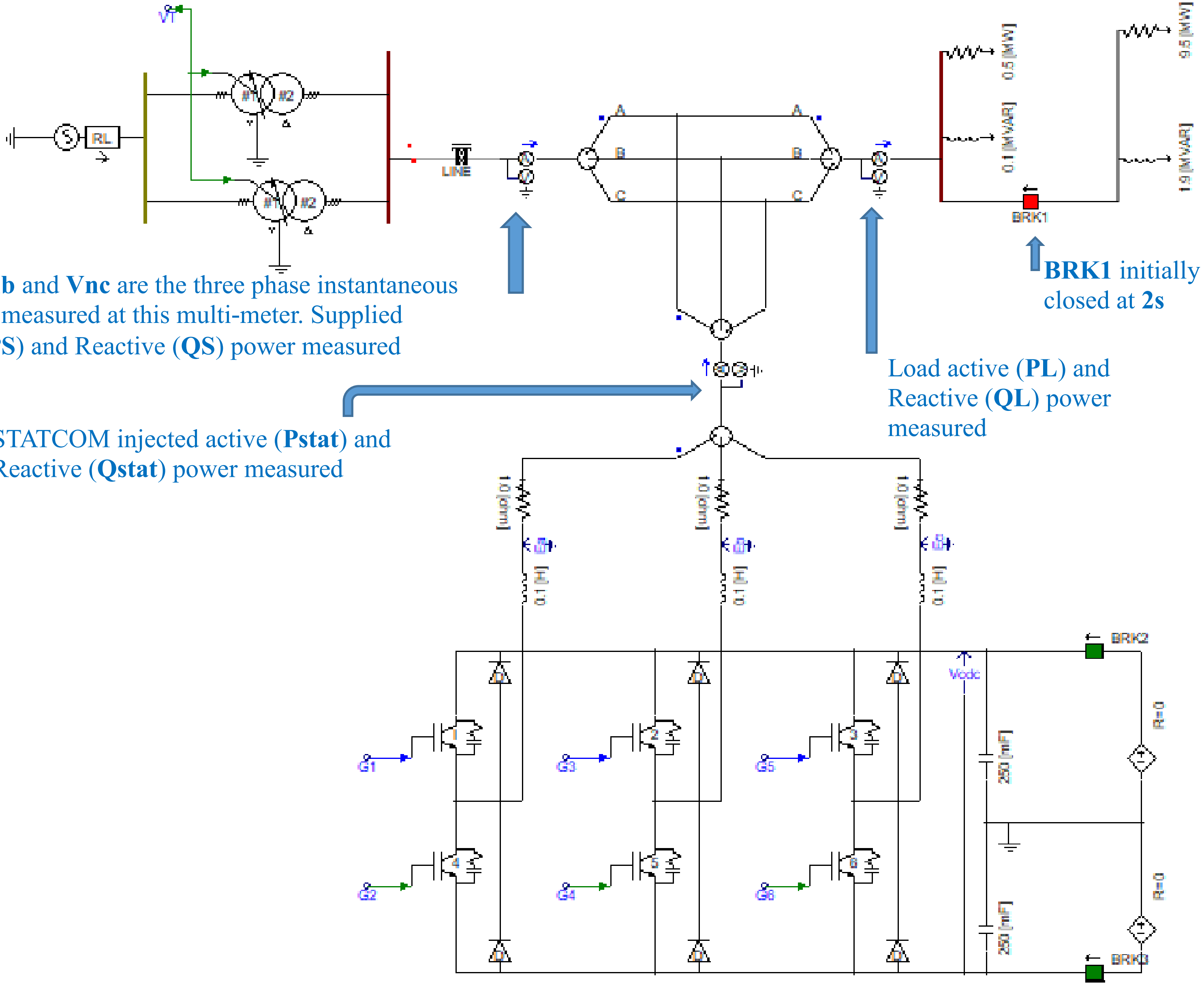


Figure 3.19 Converter Control Triangular wave and corresponding IGBT Pulse.

3.3.8 Connection of STATCOM with the simple network

STATCOM was connected to the simple network. This is shown in figure 3.20. Here the STATCOM injects active and reactive power are ‘Pstat’ and ‘Qstat’. The active and the reactive power absorbed by the load are ‘PL’ and ‘QL’. The active and reactive power supplied by the Grid source measured at the end of the distribution line are ‘PS’ and ‘QS’.



Vna, **Vnb** and **Vnc** are the three phase instantaneous voltages measured at this multi-meter. Supplied active (**PS**) and Reactive (**QS**) power measured

BRK1 initially open closed at **2s**

Load active (**PL**) and Reactive (**QL**) power measured

STATCOM injected active (**Pstat**) and Reactive (**Qstat**) power measured

Figure 3.20 STATCOM connection with the simple network.

3.3.9 Simulation results

STATCOM internally calculated reference voltages Va, Vb and Vc can be observed in figure 3.21. These three phase voltages are used by the comparator for comparison with the triangular wave form.

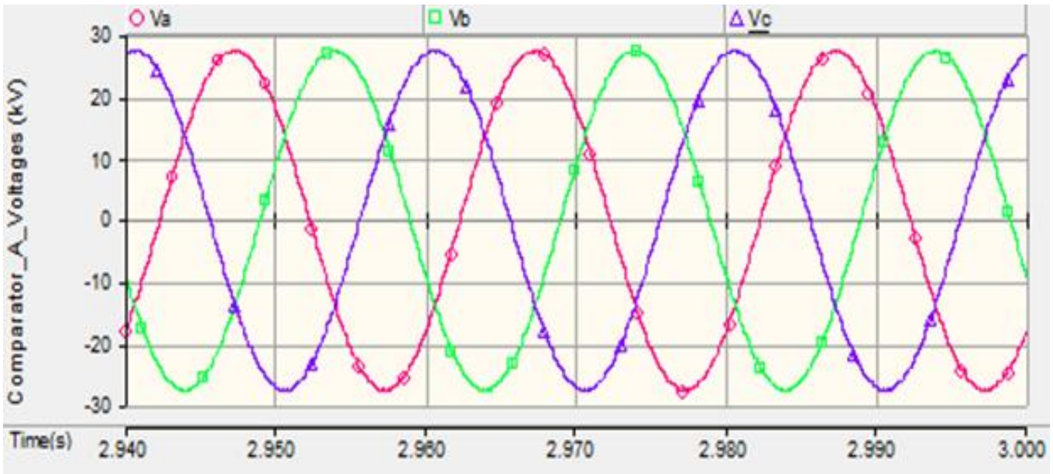
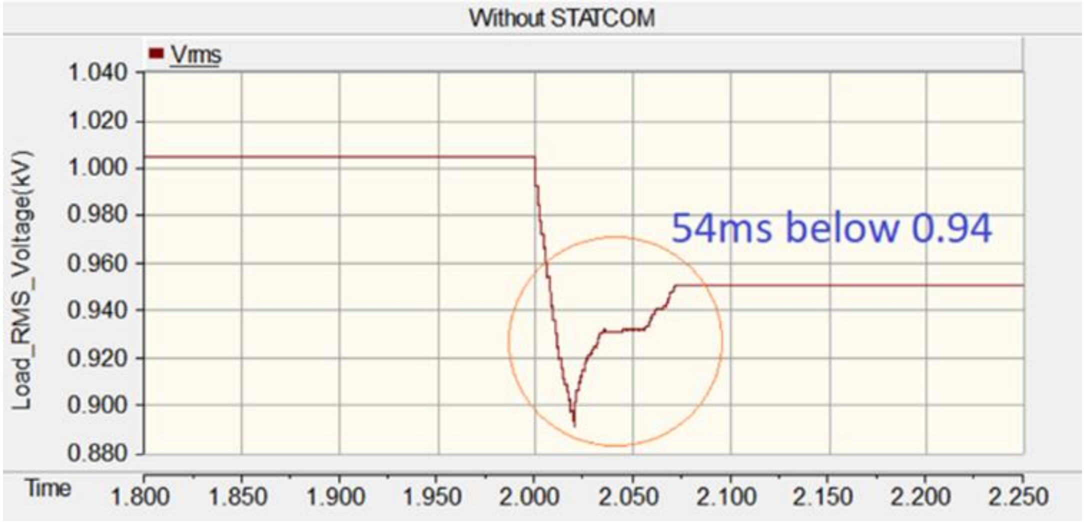
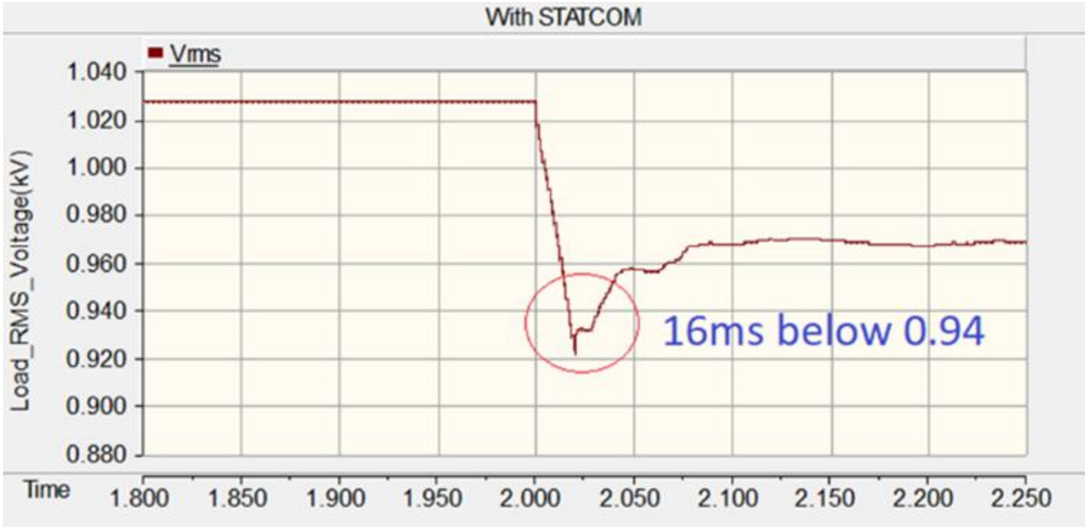


Figure 3.21 STATCOM internally calculated referenced voltages Va, Vb and Vc.

In the simple network shown in figure 3.20, BRK1 closed at 2 second caused a sudden load increment, because of all these, Vrms try to go below 0.94pu. But the OLTC together with STATCOM AC voltage Droop control operated and bring the voltage above 0.94.



(A)



(B)

Figure 3.22 Duration of time, when Vrms below 0.94pu. (A) without STATCOM and (B) with STATCOM

Figure 3.22 shows the duration of time, when Vrms below 0.94pu. (A) without STATCOM and (B) with STATCOM. This confirms that STATCOM Droop control is working with OLTC and maintaining the Voltage within the limit.

Variation of Delta, DC link Voltage and STATCOM Active Power at 2s.

The angle ‘Delta’ controls the DC Link voltage and hense the STATCOM Active Power supply to the Network. Figure 3.23 shows that, in average ‘Delta’ reduces and the Active power is absorbed by the STATCOM and the DC Link voltage brought back to its normal value. This confirms that the regulatory control is working to maintain the DC-Link voltage by varying the active power component of the STATCOM.

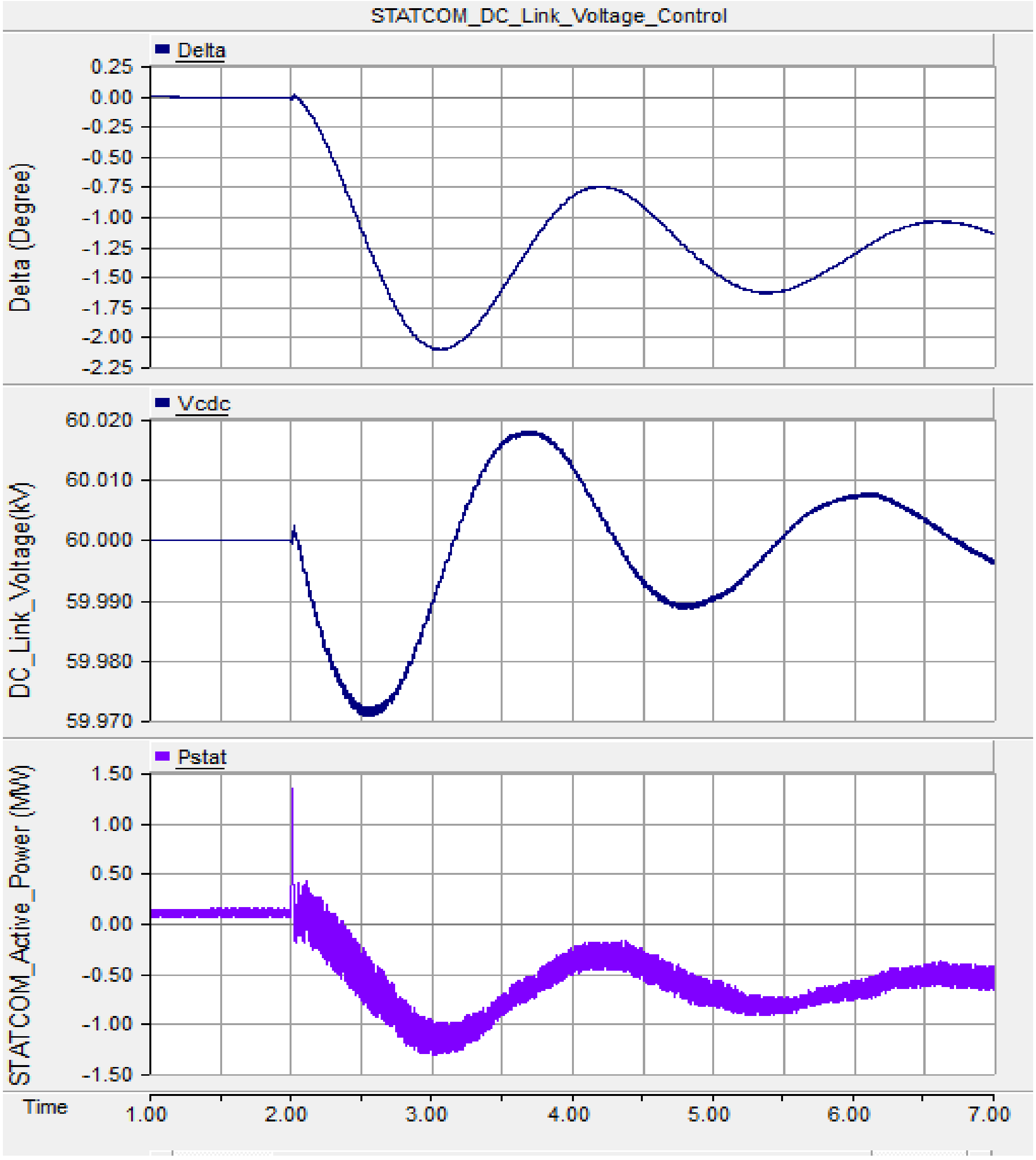


Figure 3.23 Control of DC-Link voltage

Active and reactive power variation of Load, Source and STATCOM at 2s

As shown in figure 3.20, BRK1 closed at 2 second caused a sudden load increment, that is the load active power increased from 0.5MW to 10MW and the load reactive power increased from 0.1MVAr to 2MVAr.

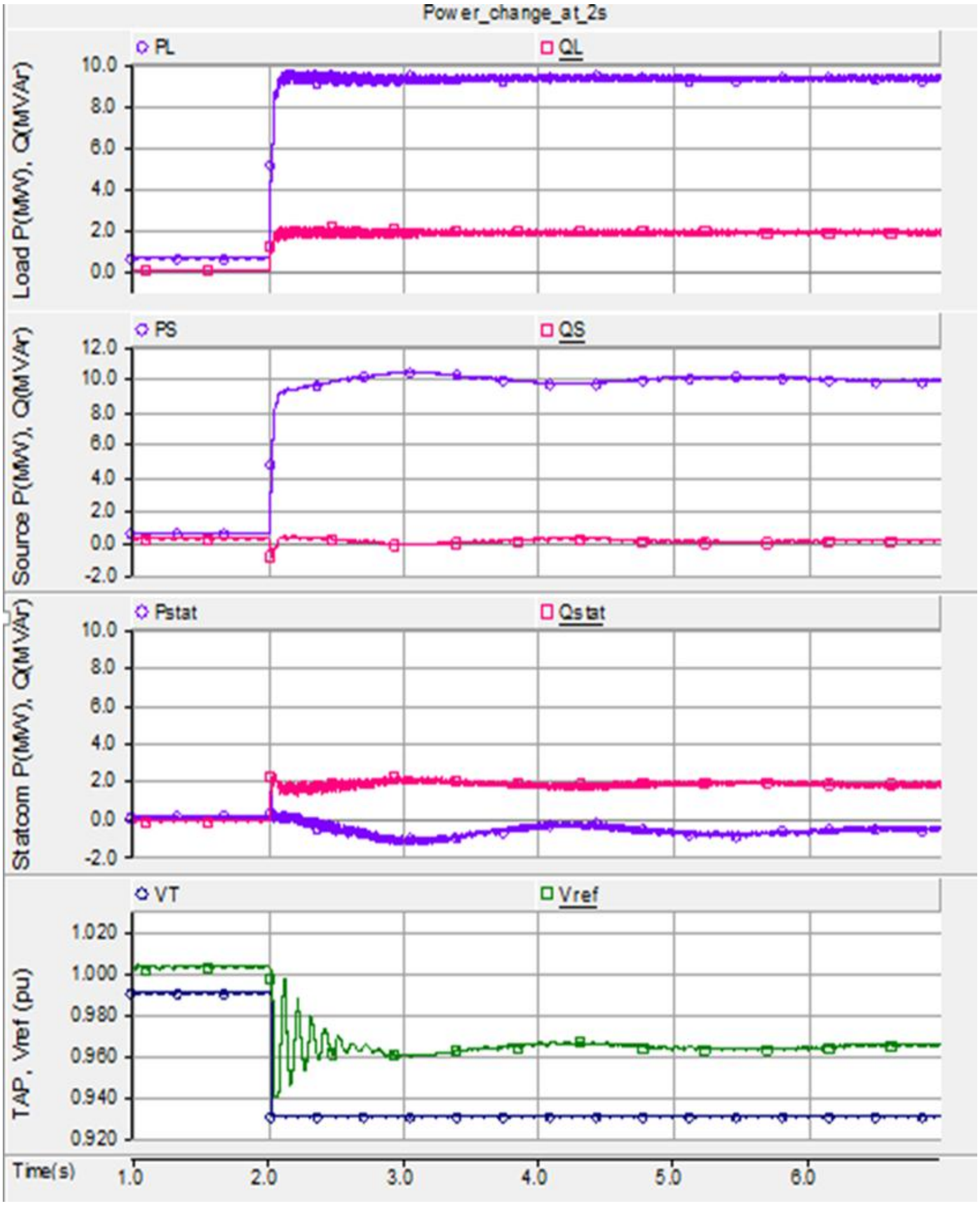


Figure 3.24 Source, Load and STATCOM active and reactive power variation.

But the STATCOM Droop control operated to bring the Vrms voltage above 0.94pu and also at 2 second the OLTC tap value at the primary side changed from 0.99pu to 0.93 pu. The variations of Vref of the STATCOM droop control, the OLTC tap changer tap value, active and reactive power of load, source and the STATCOM can be seen in figure 3.24.

The above simulation results confirmed that the fast voltage variations can be eliminated by the STATCOM with the proposed control technique.
However, from the literature, it was realized that the STATCOM is more economical only when it is required for eliminating fast variations in the voltage. This study was done as it will be required in the future. Because Sri Lanka has huge potential for electricity generation from the renewable energy technologies and therefore it will be required in the future

4

Performance of Jaffna distribution network together with STATCOM & OLTC

This chapter study the performance of the Jaffna distribution network together with STATCOM and OLTC. This was done by considering the future increased load.

(This extended study was done as per the examiners' request.)

In chapter 3, Figure 3.22, showed the transient operation of the STATCOM. This was done with the operation of the OLTC. It can be seen that when the Vrms voltage go below 0.94pu, that is the voltage spike, very faster mitigated by the operation of fast acting STATCOM.

In chapter 3, Table 3.3, showed the steady state line to line voltages at the feeders with the upper stream transformers' tap value of 0.9 and up to 160% of the peak load conditions. The second column of this table showed the worst case scenario that is 160% of peak load condition. It can be seen that the steady state voltages at 'feeder12' (0.9292 pu) and 'feeder6' (0.9130 pu) are out of acceptable tolerance limits. This worst case scenario was taken in this chapter and studied further together with the STATCOM to understand the steady state operation of the Jaffna distribution network.

4.1 Placement of STATCOM.

Table 3.3 showed voltage violations at 'feeder12' (0.9292 pu) and 'feeder6' (0.9130 pu) with the OLTC, tap value of 0.9 and 160% of the peak load condition. Here steady state voltage of feeder 12 can be increased by setting the DETC value at the primary substation transformers to 0.95. Therefore the

STATCOM was placed at ‘feeder6’ and the performance of the system was studied.

Table 4.1: Steady state line to line voltages at the feeders with chunnakam OLTC tap value of 0.9 and 160% of the peak load condition, With STATCOM at ‘feeder6’.

Distribution Line	Steady state Voltage(pu), with 160% of PEAK load with OLTC tap 0.90	
	Simulation Result	
	Without STATCOM	With STATCOM
CHU33Bus	1.0144	1.0186
Feeder 1	0.9895	0.9937
Feeder 5	1.0121	1.0164
Feeder 7	0.9998	1.0040
Feeder 3	1.0059	1.0101
Feeder 10	0.9876	0.9917
Feeder 8	1.0003	1.0045
Feeder 12	0.9292	0.9798
Feeder 2	0.9461	0.9500
Feeder 6	0.9130	0.9411
Feeder 4	0.9452	0.9492
Feeder 11	0.9475	0.9514
Feeder 13	0.9412	0.9439

The above value was derived by varying the Qmax of the STATCOM droop control. The above result was achieved with Qmax value of 4MVAr.

Therefore, 4MVAr is the capacity of the STATCOM needed to achieve this performance.

4.2 Performance of the Jaffna distribution network without STATCOM by changing the cable type from Racoon to ELM conductor with increasing load.

Future demand growth also can be done by changing the cable type from ELM to Racoon. This is discussed under the section 3.1.2, that is under the topic of ‘possible solutions which can be applied for future demand growth’. Changing the conductor type from Racoon to ELM for ‘Feeder 6’ (12.25km line segment), ‘Feeder 9’ and ‘feeder 2’ will improve the performance of the distribution systems.

This study consider the above changes and study the steady state voltage violations with increasing load. This was done without changing the tap value of DETC at the primary transformers. Only with 0.9 tap value at Chunnakam substation 31.5MVA transformers.

Table 4.2 shows the steady state voltages at the feeders with chunnakam OLTC tap value of 0.9 and 160% of the peak load condition, this study was done only changing some feeder cable types. This shows that maximum 160% of the peak load can be managed with this arrangement. After that under voltages appeared in some feederswith 170% peak load condition. Under voltage at Feeder 4 can be managed by DETC but Feeder 6 do not have that option.

Table 4.2: Steady state line to line voltages at the feeders with chunnakam OLTC tap value of 0.9 and 160% of the peak load condition, by changing cable type of some feeders.

Distribution Line	Steady state line to line Voltage(pu), Simulation Result	
	160% of PEAK load with tap 0.90	170% of PEAK load with tap 0.90
CHU33Bus	1.0144	1.0116
Feeder 1	0.9896	0.9853
Feeder 5	1.0121	1.0092
Feeder 7	0.9998	0.9961
Feeder 3	1.0059	1.0026
Feeder 10	0.9876	0.9832
Feeder 8	1.0003	0.9967
Feeder 12	0.9530	0.9465
Feeder 2	0.9802	0.9753
Feeder 6	0.9433	0.9364
Feeder 4	0.9452	0.9384
Feeder 11	0.9475	0.9407
Feeder 13	0.9652	0.9595

4.3 Performance of the Jaffna distribution network with STATCOM and Breaker Switch Capacitor (BSC)

The above discussed 170% of the peak load can be managed by using 4MVAr STATCOM at feeder 6 and 1MVAr Breaker Switched Capacitor at feeder13. This is shown in table 4.3. This solution was analyzed because even the increased capacity of STATCOM at Feeder6 does not improve the voltage at feeder 13 within acceptable tolerance limits.

Table 4.3: Steady state line to line voltages at the feeders with chunnakam OLTC tap value of 0.9 and 170% of the peak load condition, when 4MVAr, STATCOM connected at Feeder 6 and 1MVAr BSC at feeder13.

Distribution Line	Steady state Voltage (pu), with 170% of PEAK load and with OLTC tap 0.90	
	Simulation Result	
	4MVAr STATCOM connected at Feeder 6 and DETC value 0.95 at Primary substation	4MVAr STATCOM connected at Feeder 6 and DETC value 0.95 at Primary substation with 1MVAr BSC at feeder13
CHU33Bus	1.0175	1.0184
Feeder 1	0.9911	0.9920
Feeder 5	1.0151	1.0161
Feeder 7	1.0020	1.0029
Feeder 3	1.0084	1.0094
Feeder 10	0.9890	0.9899
Feeder 8	1.0025	1.0035
Feeder 12	0.9732	0.9780
Feeder 2	0.9448	0.9457
Feeder 6	0.9406	0.9411
Feeder 4	0.9462	0.9471
Feeder 11	0.9462	0.9471
Feeder 13	0.9384	0.9456

Here the feeder which serves sensitive loads can be considered for STATCOM if not breaker switched capacitor is an option.

5

Conclusion

The study proposed various methods to mitigate voltage voilations in distribution system network. This was done in three sectionsusing de-energized tap changer, on-load tap changer and the STATCOM to improve the performance of the distribution system

As a result the first contribution through this research is:

Here a method was developed to calculate the tap position, which avoid the under voltage problem in a distribution system network (The case study was done with Jaffna distribution system network).Thismethod was elaborated by an equation to calculate the tap value of the transformer.

This is to bring the operation of the transformer output voltage to the middle region when the load varies from off peak to peak.

Finaly the method was validated by the simulation. The simulation results confirmed that all under voltage violation was completely eliminated by this proposed technique.This method also helped to maximize the usage of existing transformers in fixed tap position which avoid any transients in its operations.

The second contribution through this research is:

A method was studied on when and how to use the OLTC to avoid the under voltage problem in a distribution system network.To check the performance of the OLTC, a customized and automatic control technique to operate the OLTC tap positions was developed.

The operational concept of the OLTC with the developed control technique was verified in the simulation with a simple network model(because the study shown that the existing Jaffna distribution network does not require the OLTC). The simulation results confirmed that the voltage violations were eliminated, whenever it reaches to the voltage limits and the OLTC operations, brought the system back to its safe region.

The third contribution through this research is:

A STATCOM model was developed with an AC terminal voltage droop control and a DC Link Voltage Regulatory control to eliminating the voltage violations during the transient operations OR fast variations on voltage.

The developed system control technique was checked in the simulation using the STATCOM model. The simulation results confirmed that the fast voltage variations can be eliminated by the STATCOM with the proposed control technique. A Phase Locked Loop was developed to identify the phase angle and Park Transformation was used to identify the phase error.

However, from the literature, it was realized that the STATCOM is more economical only when it is required for eliminating fast variations in the voltage. This study was done as it will be required in the future. Because Sri Lanka has huge potential for electricity generation from the renewable energy technologies and therefore it will be required in the future.

Contribution through this research by sharing with others:

A full paper (seven pages) was presented and published at the IET Sri Lanka Section Conference, which was held in 2018. This gave an excellent opportunity for sharing the research findings with other researchers.

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