

POWER EVACUATION STUDIES FOR GRID INTEGRATED WIND ENERGY CONVERSION SYSTEM

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Dr. R.P.Kumudini Devi
Dr.P.Somsundaram
Mrs.S.V.Anbuselvi

Associate Professor
Associate Professor
Associate Professor

Department of Electrical and Electronics Engineering
Anna University
Chennai – 600025

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Major contributors in alphabetical order include :

Anbuselvi.S.V	Associate Professor
Kumudini Devi.R.P	Associate Professor
Somsundaram.P	Associate Professor

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ABBREVIATIONS

WTGs	Wind turbine generators
IG	Induction generator
FACTS	Flexible AC Transmission Systems
TCSC	Thyristor Controlled Series Compensator
VSC	Voltage Source Converter
HVDC	High Voltage Direct current
PWM	Pulse Width Modulation
WECS	Wind energy conversion systems
LVRT	Low Voltage Ride Through

LIST OF SYMBOLS

f	Operating Frequency, 50Hz
R_a	Armature resistance of the synchronous machine
X_d	Synchronous reactance of d-axis winding of the synchronous machine
x_d'	Transient reactance of d-axis winding of the synchronous machine
X_q	Synchronous reactance of q-axis winding of the synchronous machine
X_q'	Transient reactance of q-axis winding of the synchronous machine
T_{d0}'	Open circuit time constant of the d-axis winding of the synchronous machine
T_{q0}'	Open circuit time constant of the q-axis winding of the synchronous machine
δ	Load angle in degree
E'	Internal voltage of synchronous machine
R_s	Stator resistance of induction machine
R_r	Rotor resistance of induction machine
X_s	Stator leakage reactance of induction machine
X_r	Rotor leakage reactance of induction machine
X_m	Magnetizing reactance of induction machine
I_1	Stator current of induction machine
I_2	Rotor current of induction machine
V	Terminal voltage of induction machine
s	Slip
N_t	Number of wind turbine generators
E'_r E'_m	Internal voltages of induction machine
P_g	Air gap power
θ	Pitch angle
ω	Wind turbine shaft speed
R	Radius of the wind turbine rotor

ω_s	Synchronous speed
ω_r	Angular speed of the rotor
λ	Tip speed ratio
I_{Norton}	Norton current source
α^0	Initial Firing angle of TCSC
α	Firing angle of TCSC
P_{spec}	Specified real power flow at HVDC terminal
Q_{spec}	Specified reactive power flow at HVDC terminal
P_{HVDC1}	Calculated real power flow at converter 1.
P_{HVDC2}	Calculated real power flow at converter 2.
Q_{HVDC1}	Calculated reactive power flow at converter 1.
Q_{HVDC2}	Calculated reactive power flow at converter 2.
Z_{VR}	Impedence of converter transformer
Y_{VR}	Admittance of converter transformer
V_k	AC voltage at bus k
θ_k	Voltage angle at bus k
$\bar{V}_{\text{VR}}$	Voltage at fictitious bus
δ_{VR}	Voltage angle of fictitious bus
X_{TCSC}	TCSC equivalent reactance
Z	Bus impedance matrix
Y	Bus admittance matrix
B	Susceptance
H_t	Inertia of the turbine
H_g	Inertia of the generator

TERMS OF REFERENCE

A project team from Anna University is formed to analyze the power evacuation problems for grid integrated wind energy conversion system. Accordingly a project proposal was submitted to Center for Wind Energy Technology (C-WET), Chennai. C-WET had allotted a project namely “Power Evacuation Studies for Grid Integrated Wind Energy Conversion System” to the Head of the Department of Electrical and Electronics Engineering (DEEE) through appropriate authorities of Anna University (AU) to study the Power Evacuation for a part of southern grid (Tirunelveli /Tamil Nadu). A project team was formed whose composition is given below:

- | | |
|--|-------------------------------|
| 1. Dr.R.P.Kumudini Devi, Associate Professor, DEEE, AU. | Principal Investigator |
| 2. Dr.P.Somasundaram, Associate Professor, DEEE, AU. | Co-Investigator |
| 3. Mrs.S.V.Anbuselvi, Assistant Professor, DEEE, AU. | Co-Investigator |

SCOPE OF WORK

The project was agreed to be executed in following five phases:

- **Phase I:** To collect the data for the particular area in TNEB grid through field visit.
- **Phase II:** To model the wind turbine generators (WTGs) for power flow studies and develop source code by considering suitable model for squirrel cage induction generator.
- **Phase III:** To model the wind turbine generators for short circuit studies and to identify the weak and strong points for addition of WTGs.
- **Phase IV:** To model the TCSC and VSC based HVDC system for power flow studies and to analyze the enhancement of power evacuation from WTGs.
- **Phase V:** To develop a transient stability model of WTGs and to analyze the system stability with wind energy conversion system (WECS).

EXECUTIVE SUMMARY

- Tirunelveli region is considered for the analysis. The data pertaining to this region is collected through field visits.
- Power flow analysis is carried out for two different cases by varying the wind power penetration from 40% to 80% of the installed capacity and the over loaded transmission lines are identified.
- Short circuit analysis is carried out without WTGs to determine the fault level. The strong buses are identified for the future capacity addition in this region. Addition of WTGs can be avoided to the identified weak buses
.
- Power flow analysis is carried out with TCSC and VSC based HVDC system for future expansion of WTGs installation and to alleviate the power evacuation problems.
- Transient stability analysis with WTGs is carried out to study the effect of WTGs on the system stability.
- Conclusions and Recommendations are drawn based on the analysis.

ROAD MAP OF THE PROJECT

Phase	Activity Block	Time Required (in months)
I	Data collection for the particular area in TNEB grid.	6
II	- Modeling of wind Generators for power flow studies - Source code development by considering suitable model for squirrel cage Induction generator - Power flow results for the system	6
III	- Modeling of wind generators for short circuit studies - Short circuit study for system considered to identify the weak points	6
IV	- Power flow modeling of TCSC and VSC based HVDC system - Power flow study with TCSC/VSC based HVDC system	6
V	- Development of stability model for wind Energy conversion systems. - Transient stability analysis for the system considered. - Report preparation and training for Practicing Engineers.	6
	Duration: 30 months	

1. INTRODUCTION

In the year 2010-11, the installed capacity of wind generators is 7134 MW (as on 31-09-2012) and an additional capacity of 6000 MW targeted under 12th five year plan by the Department of Energy , Government of Tamil Nadu. The additional wind power generation may require enhancement in the line capacity and VAR compensation in the grid. Therefore power evacuation studies are necessary to assess the technical feasibility of the grid to evacuate wind power from wind turbine generators. Power evacuation studies comprise of Power flow, short circuit and transient stability studies.

Planning, operation and control of WTG integrated power systems poses a variety of challenging problems. The solution of which requires extensive analysis of power system with WTGs. This project aims at carrying out the power flow, short circuit and transient stability studies for a part of Tamil Nadu grid with WTGs.

Power-flow studies are of great importance in planning and designing the future expansion of power systems as well as in determining the best operation of existing systems. The principal information that can be obtained from the power flow analysis is the reactive power consumption and loading of lines with respect to the wind power penetration. Short-circuit studies are essential to arrive at the possible locations for future wind power penetration to the grid. Transient stability analysis of the power system with WTGs is necessary as it provides the information regarding the fault ride through/low voltage through capabilities of WTGs.

From literature, it is noted that power transfer capabilities of transmission lines and VAR management are enhanced with the help of FACTS/VSC based HVDC link. Hence an attempt is made to include the FACTS/VSC based HVDC link in the network considered for analysis.

2. FIELD VISIT AND DATA COLLECTION

2.1 Introduction

During the first field visit, the Tirunelveli network details are obtained from the Superintending Engineer, Wind Energy Development Cell, Tirunelveli. The single line diagram of wind farm and distribution substations in Tirunelveli region is shown in Figure 2.1.

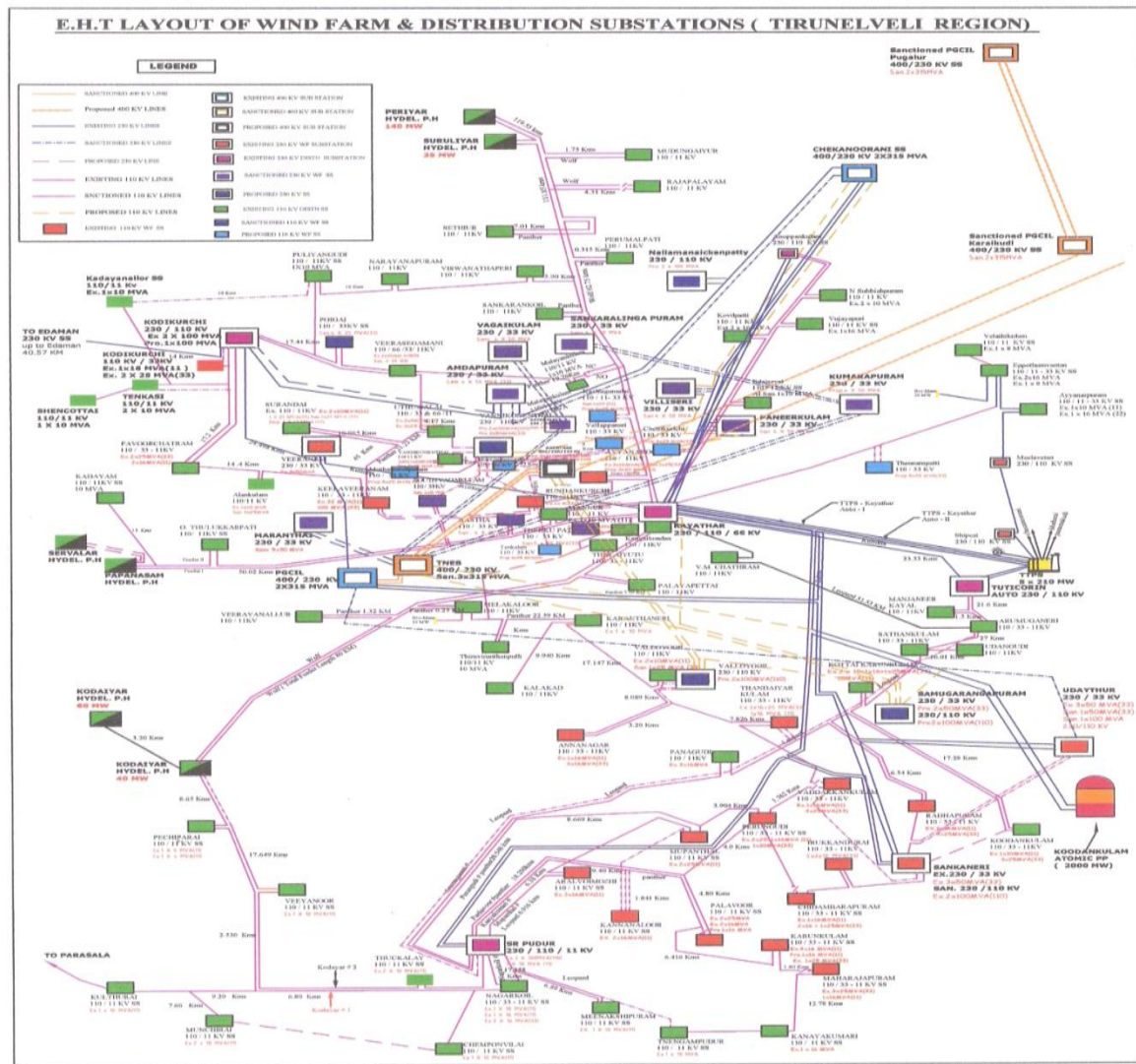


Figure 2.1 EHT layout of wind farm and distribution substations in Tirunelveli study system

Tirunelveli region consists of 44 substations out of which 22 are dedicated for wind farms. The wind farms consist of different rating of induction generators of 225kW, 250kW, 500kW, 750kW, 900kW up to 2.1MW.

The wind generators data such as rated power of each wind turbine, rated apparent power, rated wind speed, cut-in wind speed, cut-out wind speed, rated voltage, rated current, short circuit ratio, synchronous speed, rated slip, magnetizing reactance of generator, stator resistance and leakage reactance, stator reactance, rotor resistance and leakage reactance, rotor reactance are collected.

The wind turbine transformer data such as transformer voltage ratio, percentage impedance, winding connection and tap settings are collected.

In the second visit, wind farm related data like wind farm sub-station details, generation data, load data, load shedding, peak return, private generation and full returns for 2010 are collected.

The data required for analysis such as generator data, substation data, bus data, transmission line data, shunt elements data, power transformer data, load data and conductor data are collected from TANGEDCO and are tabulated in Appendix – A and Appendix – B.

2.2 Generation details in Tirunelveli region

The Tirunelveli network comprises of a mix of various generations such as thermal, hydro, biomass and wind. The conventional generation details in the Tirunelveli region are tabulated in Table 2.1.

Table 2.1 Generation details of Tirunelveli region

S.No	Generator Name	Installed capacity (MW) = (No.of units installed in MW) X (Capacity of single unit)	Total(MW)
1	Tuticorin Thermal Power Station (TTPS)	5x210	1050
2	Ind-Bharath Captive Thermal Power plant	1X210	210
3	Kodayar-I Hydro Generator	1x60	60
4	Kodayar-II Hydro Generator	1x40	40
5	Suruliyar Hydro Generator	1x35	35
6	Periyar Hydro Generator	4x35	140
7	Servalar Hydro Generator	1x20	20
8	Papanasam Hydro Generator	1x32	32
9	Biomass Eppothumventran Generator	1X21	21
10	Biomass Melakaloor Generator	1X21	21
Total			1608

2.3 Substation details in Tirunelveli region

The total installed capacity of WTGs in Tirunelveli region is 2857.70 MW (up to September 2010). The total number of wind turbine generators is 5106 (up to September 2010). The Table 2.2 shows substation-wise total number of connected wind turbine generators and their installed capacity (MW).

Table: 2.2 Substation details

Sl.No	Name of the substation	Number of WTGs	Installed capacity in MW
1	Ayyanaruthu 110/11 kV SS	174	81.78
2	Kayathar 66/11 kV SS	29	10.765
3	Chettikurichy 66/11 kV SS	3	4.4
4	Perungudi 110/33-11 kV SS	346	102.455
5	Vadakkankulam 110/33-11 kV SS	272	134.98
6	Kottaikarungulam 110/33-11 kV SS	91	65.025
7	Radhapuram 110/33-11 kV SS	180	139.215
8	Muppandal 110/11 kV SS	223	55.125
9	Panagudi 110/11 kV SS	96	47.875
10	Aralvoimozhi 110/11 kV SS	211	53.565
11	Pazhavor 110/11 kV SS	315	91.505
12	Karunkulam 110/33-11 kV SS	321	113.155
13	Koodankulam 110/33-11 kV SS	83	90.25
14	Kottaram 110/11 kV SS	15	7.45
15	Anna Nagar 110/33-11 kV SS	119	66.775
16	Sankaneri 230/110 kV SS	137	152.3
17	Chenbagaramanputhoo 110/11 kV SS	9	2.25
18	Chidambarapuram 110/33-11 kV SS	228	79.75
19	Maharajapuram 110/33-11 kV SS	136	84.73

20	Kannanallur 110/11 kV	148	36.225
21	SPIC 230 / 110 / 22 KV SS	20	1.1
22	Irukkanthurai 110/33 kV SS	26	29.2
23	Udayathur 230/110kV SS	130	196.55
24	Thandaiyarkulam 110/33-11 kV SS	170	104.2
25	Vannikonendal 66/11 kV SS	40	12.545
26	Sundankurichi 110/33-11 kV SS	104	91.5
27	Keelaveeranam 110/33-11 kV SS	324	144.275
28	Veeranam 230/33KV SS	182	201.6
29	Alankulam 110/11 kV SS	89	61.55
30	Uthumalai 110/33-11 kV SS	78	92.75
31	Surandai 110/11 kV SS	82	50.95
32	P V Chatram 110/33-11 kV SS	102	71.4
33	Kodikuruchi 110/33-11 kV SS	148	68.425
34	Tenkasi 110/11 kV SS	35	16.9
35	Shencottah 110/11 kV SS	25	10.045
36	Kadayanallur 110/11 kV SS	54	23.66
37	Veerasigamani 110/66-33-11 kV SS	221	98.57
38	Amuthapuram 230/33 kV SS	54	87.6
39	Rastha 110/33 kV SS	16	24
40	Manur 110/11KV SS	53	42.4
41	Mandapam 110/33-11 kV SS	4	0.9
42	Rameshwaram 110/11 kV SS	2	0.5
43	Gangaikondan 110/11 KV SS	1	0.055
44	Kanyakumari 110/11kV SS	10	7.45
	Total	5106	2857.70

2.4 Summary

The data required for power evacuation studies such as power flow analysis, short circuit analysis and stability analysis are collected through field visit for the Tirunelveli region.

3. POWER FLOW ANALYSIS

3.1 Introduction

The Tirunelveli network consists of 156 buses, 210 transmission lines, 44 transformers and 5106 WTGs. The network comprises of a mix of various generations such as thermal, hydro, biomass and wind. As the network consists of large number of WTGs it is necessary to go for an aggregated model to reduce the simulation time. This chapter deals with aggregated model for grid connected wind farms and power flow analysis.

3.2 Aggregated model for grid connected wind farms

Wind farms with wind turbine generators can be simulated by a complete model including the modeling of all the wind turbines and the wind farm electrical network. To represent wind turbines in wind farms without increasing unnecessarily the model order, reduced models have been used. But this complete model presents a high order model if a wind farm with high number of wind turbines is modeled and therefore the simulation time is long.

To reduce the complexity of the wind farm model and the simulation time when simulating wind farms with wind turbines in power systems, aggregated models of wind farms have been developed by the aggregation of wind turbines with identical wind into an equivalent wind turbine. The aggregation of wind turbine generators with identical wind speeds into an equivalent wind turbine generator experiencing that wind speed has been considered. This equivalent wind turbine presents the same per unit model and parameters of that of individual wind turbine generator.

The two main assumptions made while reducing the wind park to a single equivalent are:

- All wind turbines have same operating point.
- If difference in operating point exists it is not too large.

When reducing the aggregate model of the large wind farm for the purpose of simulation studies the following criteria shall be fulfilled:

- The MVA-rating (S_{Agg}) of the aggregated wind farm equivalent is the sum of the MVA- ratings of individual WTGs in the system.

$$S_{Agg} = \sum_{i=1}^{IG} S_i$$

where S_i is the MVA rating of the individual WTGs in the system.

- The wind farm equivalent supplies the same amount of electric power which is given as,

$$P_{Agg} = \sum_{i=1}^{IG} P_i$$

where P_i is the electric power supplied by individual wind turbine generator.

A simple aggregated model is considered in all the studies (Power flow analysis, Short circuit analysis and Transient stability analysis) for representing wind farms. Simple aggregation is explained by considering the Kayathar wind farm. By assuming the direction of the wind velocity as shown in Figure 3.1.a and neglecting the wake effect, the wind farm is represented by its simple aggregated model as shown in Figure 3.1.b. The parameters of WTG's in simple aggregated model is explained in Table3.1

Table3.1 Parameters of Detailed and Simple aggregated model

Sl.No	Nomenclature	Detailed model of single WTG	Simple aggregation model of wind farm
1.	Stator Resistance R_s	R_s	R_s / N_t^*
2.	Stator Reactance X_s	X_s	X_s / N_t
3.	Rotor Resistance R_r	R_r	R_r / N_t
4.	Rotor Reactance X_r	X_r	X_r / N_t
5.	Mutual Reactance X_m	X_m	X_m / N_t
6.	Inertia of the turbine - H_t	H_t	$H_t * N_t$
7.	Inertia of the generator – H_g	H_g	$H_g * N_t$
* N_t -Number of wind turbine generators			

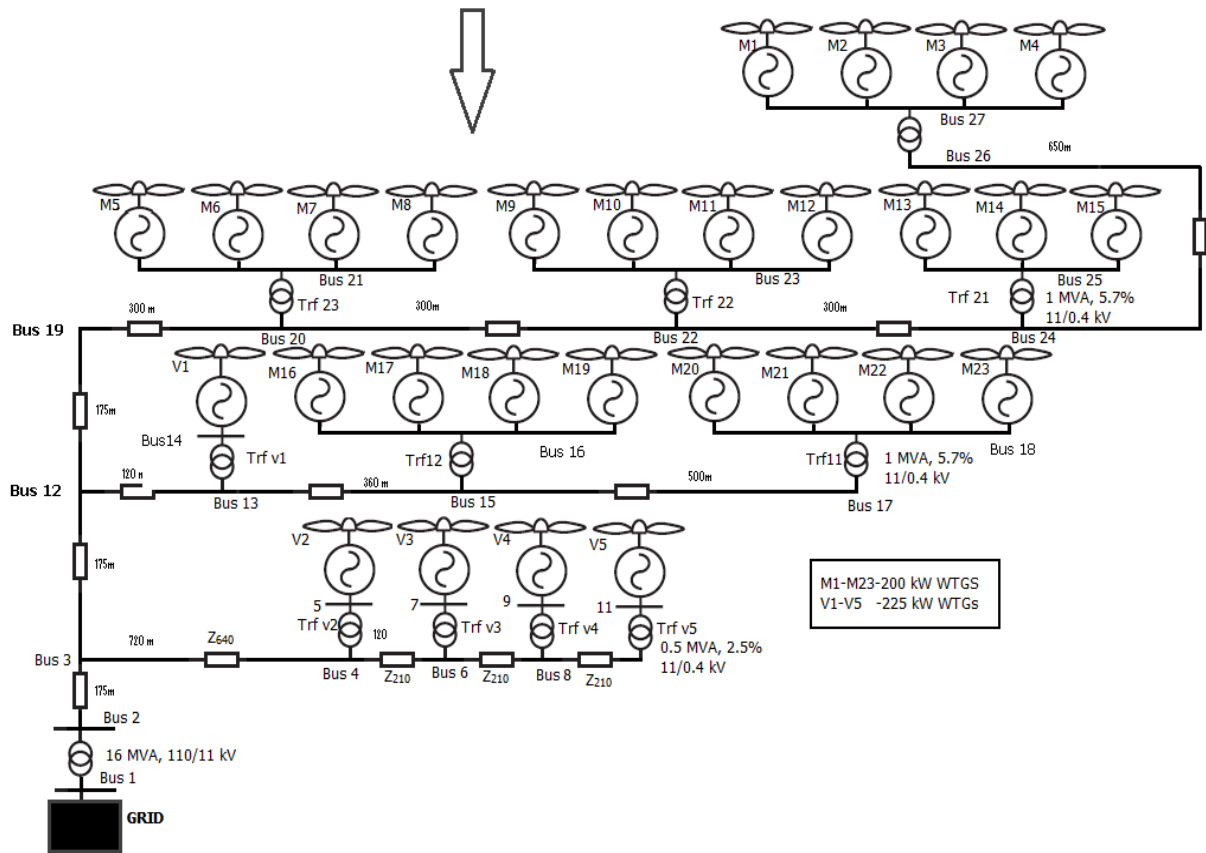


Figure 3.1.a One line diagram of Kayathar wind farm

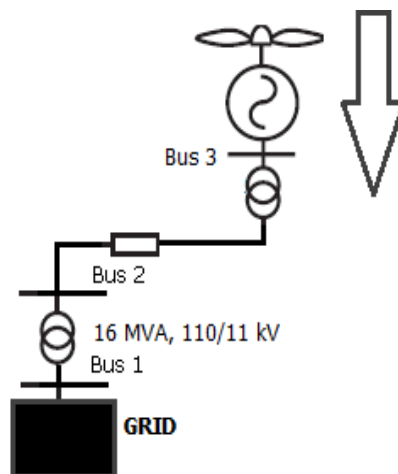


Figure 3.1.b Simple aggregation of Kayathar wind farm.

3.3 Voltage profile and line over loading

The power flow analysis is conducted for following cases:

- Case 1: 100% Hydro with nil wind power generation
- Case 2: 100% Hydro with different levels of wind power penetration.

Power flow analysis is carried out for two different cases by varying the wind power penetration from 40% to 80% of the installed capacity and the over loaded transmission lines are identified.

Case 1: 100% Hydro and nil wind power generation

In this case, Thermal generators meet the base load and the hydro generators are considered at maximum generation (six generators). The wind generation is nil. Only three lines are loaded between 75% to 100%.

Case 2: 100% Hydro with different levels of wind power penetration

The load flow analysis is carried out by varying the wind power penetration from 40% to 80% of the installed capacity of 2857.70 MW (up to September 2010).

a) Power flow with 40% wind power penetration:

Considering full hydro and up to 40% of wind power penetration, none of the transmission lines are overloaded and the voltage profile is good throughout the network.

b) Power flow with 50% wind power penetration:

Considering full hydro and 50% wind power penetration,

- Wind power penetration into the grid is 672.20 MW.
- Eight Transmission Lines are loaded from 75% to 100%.
- Low voltage is observed at PARAMAGUDI SS as 0.9352 p.u.
- Total reactive power compensation of 120.56 MVAR is provided.

c) Power flow with 70% wind power penetration

Considering full hydro and 70% wind power penetration, the lines that are overloaded are given in Table 3.2.

Table 3.2 Overloaded transmission lines at 70% of wind power penetration

Lines		MW	MVAR	% Loading	Rating (MVA)
From substation	To substation				
SANKANE2	SANKAN21	-224.571	12.959	115	200
UDAYTHR2	UDAYTR21	-200.807	19.35	103	200
RADHAPUR	KOTTAIKA	89.481	-10.714	102	90
MUPPTOFF	PERUNGUD	-92.156	7.071	104	90
KAYATR21	AYYANARO	-96.253	-6.917	110	90
KOTTAIKA	SATHANK	108.734	-21.852	127	90
KEELAVEE	KAYATR21	104.289	3.75	115	90
SATTURTF	OTHULUKK	-93.699	14.406	109	90
MALAYTOF	MALAYANK	-70.729	7.416	102	90

d) Power flow with 80% wind power penetration

Considering full hydro and 80% wind power penetration, the lines that are overloaded are given in Table 3.3. Low voltage profile observed at four buses.

Table 3.3 Overloaded transmission lines at 80% of wind power penetration.

Lines		MW	MVAR	% Loading	Rating (MVA)
From substation	To substation				
SANKANE2	SANKAN21	-262.925	14.588	136	200
UDAYTHR2	UDAYTR21	-234.852	21.478	122	200
SRPUDU21	ARALVOIM	-92.847	12.958	107	90
SATHANK	ARUMUGAN	86.22	-28.587	105	90

RADHAPUR	KOTTAIKA	99.843	-20.72	115	90
VALLIYUR	ANNANAGA	-87.046	26.12	103	90
VALLIYUR	KARANTHA	84.086	-28.121	101	90
VEERASEG	UTHUMALA	-91.679	-8.749	102	90
SRPUDU21	MUPPTOFF	-100.62	3.807	115	90
SRPUDU21	PERUTOFF	-98.317	3.803	113	90
PALATOFF	KARUNKUL	-90.018	4.648	101	90
MUPPTOFF	PERUNGUD	-104.403	8.673	118	90
KAYATR21	AYYANARO	-112.464	-2.389	129	90
KOTTAIKA	SATHANK	124.943	-29.038	147	90
KEELAVEE	KAYATR21	120.458	-0.058	133	90
ANUPPA21	SATTURTF	-91.762	23.633	109	90
SATTURTF	OTHULUKK	-105.146	17.486	122	90
MALAYTOF	MALAYANK	-74.931	11.82	109	90

3.4 Reactive power requirement

The reactive power compensation required for different levels of wind power penetration is shown in Figure 3.2

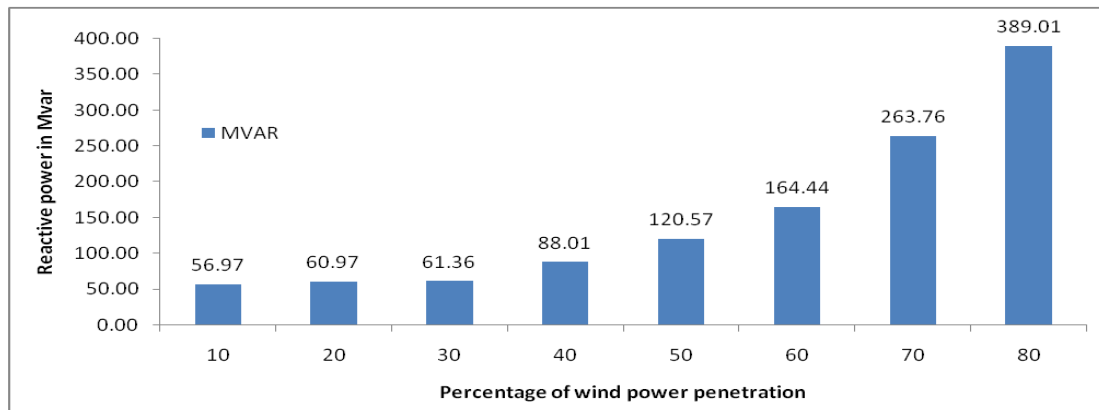


Figure 3.2 Percentage of wind power penetration Vs required reactive power

3.5 Real power losses

The real power loss with different levels of wind power penetration is shown in Figure 3.3

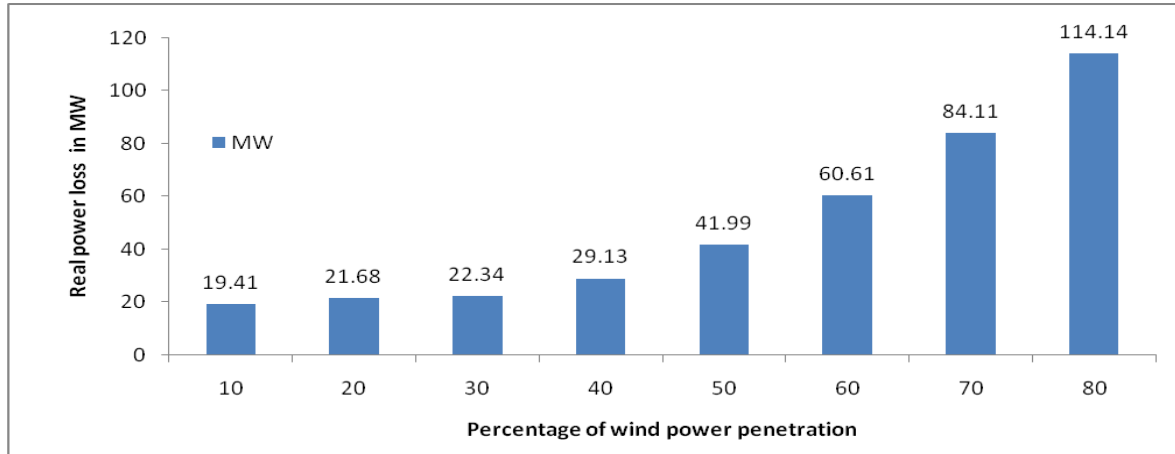


Figure 3.3 Percentage of wind power penetration Vs real power losses

3.6 Summary

Power flow analysis is carried out for Tirunelveli network with WTG's and it is observed that increasing wind power penetration leads to overloading of more number of the transmission lines and transformers.

4. SHORT CIRCUIT ANALYSIS

4.1 Introduction

Short circuit analysis of Tirunelveli system is performed to identify weak buses and strong buses in the system under disturbance. The possibilities for a short circuit in three-phase system are as follows

- a. Symmetrical three phase-to-ground fault
- b. Symmetrical three phase fault
- c. Single-line-to-ground(LG) fault
- d. Line-to-line(LL) fault
- e. Double-line-to-ground(LLG) fault

Fault of the type (a) and (b) have a symmetric impedance and/or admittance representation. Hence, for faults of these types, the system becomes a balanced three-phase network with balanced excitation. Analysis of such balanced three-phase networks can be carried out on the basis of a per phase equivalent, except that the impedances are now replaced with 'Positive sequence' impedances. In the case of unsymmetrical faults-type (c), (d), and (e) such a simplified analysis is not possible and the analysis is either carried out through sequence components.

4.2 Short circuit assumptions

In arriving at a mathematical model for short-circuit studies, a number of assumptions are made which simplify the formulation of the problem and in addition, facilitate the solution without introducing significant inaccuracies in the results. The main assumptions are as follows:

1. The normal loads, line charging capacitances and other shunt connections to ground are neglected. This is based on the fact that the faulted circuit has predominantly lower impedance than the shunt impedances. The saving in computational effort as a result of this assumption justifies the slight loss in accuracy
2. The generator is represented by a voltage source in series with a reactance that is taken as the sub- transient or transient reactance. Such a representation is adequate to compute the magnitudes of currents in the first 3-4 cycles after the fault occurrence.

3. All the transformers are considered to be at their nominal taps.
4. Since the resistances of the transmission lines are smaller than the reactance by a factor of five or more, they are neglected.

4.3 Systematic computation for large scale systems

The systematic computation procedure to be used for fault analysis of a large power systems using computer is explained below. Let us consider a symmetric fault at bus r of an n -bus system. Let us assume that the pre-fault currents are negligible.

Step 1: Draw the pre-fault per phase network of the system (positive sequence network) .Obtain the positive sequence bus impedance matrix, Z using Bus building algorithm. All the machine reactances should be included in the Z bus.

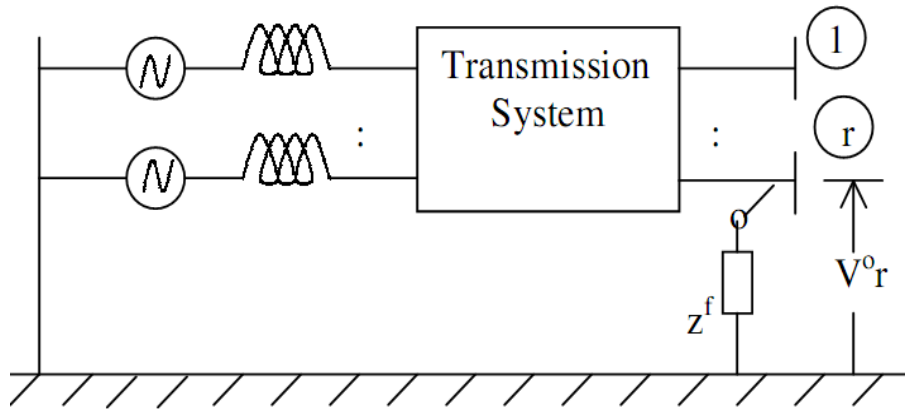


Figure 4.1 Single Line diagram with symmetrical fault

The pre-fault bus voltage vector is given by

$$\mathbf{V}^o = \begin{bmatrix} V_1^o \\ V_2^o \\ \vdots \\ V_n^o \end{bmatrix} \quad 4.1$$

Step 2: Obtain the fault current using the Thevenin's equivalent of the system feeding the fault as explained below. Assume fault impedance as Z^f . The Thevenin's equivalent of the system feeding the fault impedance is given in Figure 4.2. The fault current is given by

$$I^f = V_r^0 / (Z_{rr} + z^f)$$

4.2

where Z_{rr} is the rr^{th} diagonal element of the bus impedance matrix.

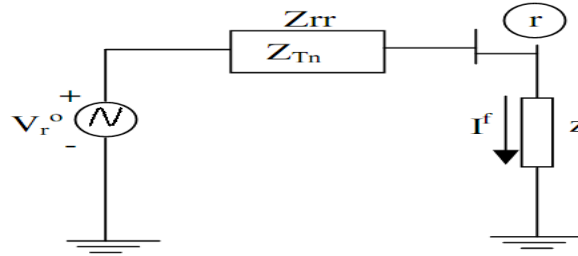


Figure 4.2 Thevenin's Equivalent of the system feeding the fault

Step 3: Obtain the Thevenin's equivalent network by inserting the Thevenin's voltage source V_r^0 in series with the fault impedance and compute the bus voltages using network equation as explained below.

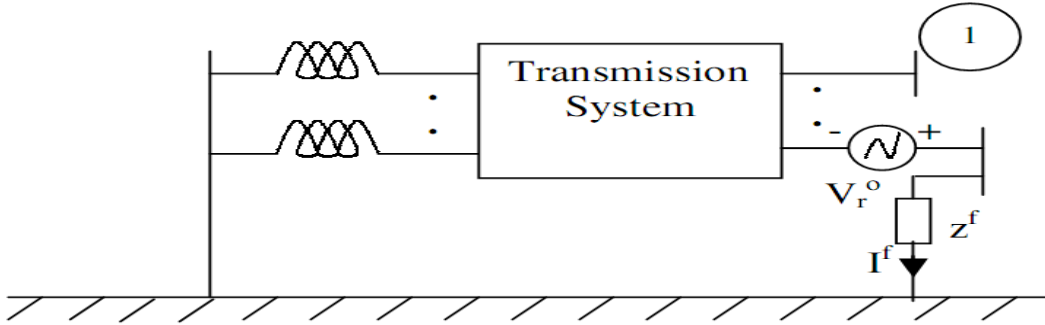


Figure 4.3 Thevenin's Network

The change in bus voltages, V_T caused by the fault at bus r is given by

$$V_T = Z I^f$$

4.3

where,

Z = Bus impedance matrix of Thevenin's network including machine reactance

I^f = bus current injection vector

$$\mathbf{I}^f = \begin{bmatrix} \mathbf{0} \\ \vdots \\ -\mathbf{I}^f \\ \vdots \\ \mathbf{0} \end{bmatrix}_r \quad 4.4$$

Step 4: The post fault bus voltages are given by super-position of equations

$$\mathbf{V}^f = \mathbf{V}^0 + \mathbf{V}_T \quad 4.5$$

$$\mathbf{V}^f = \mathbf{V}^0 + \mathbf{Z}\mathbf{I}^f \quad 4.6$$

Expanding, the above equation and substituting for $\mathbf{I}^f$, we get the post fault voltages as

$$V_1^f = V_1^0 - Z_{1r} I^f$$

•

•

$$V_n^f = V_{no} - Z_{nq} I^f$$

The post fault line currents are given by $I_{ij}^f = (V_i^f - V_j^f) / Z_{ij} \quad 4.7$

4.4 Strong and weak buses without wind farms

The fault level of system without considering wind power generation is used to identify the strong buses and weak buses.

4.4.1 Strong buses in the system

The fault level without WTGs are computed and strong buses are identified if fault current is greater than 10 p.u and the strong buses are tabulated in Table-4.1.

Table 4.1 Strong buses in Tirunelveli system.

Bus No	Bus Name	Fault Level (pu)
1	TTPS_GENERATOR	11.1773
2	IBCPPGENERATOR	10.4535
3	SANKANERI	10.2438
4	UDAYTHUR	10.1029
5	TUTICORIN_AUTO	11.4373
6	ABESEKAPATTI	10.4849
7	KAYATHAR	11.4743
8	TTPS_SWITCHYARD	11.6165
9	STERLITE	10.4891
10	SIPCOT	11.4637
11	ANUPPANKULAM230	10.3857
12	CHEKKANOORANI	11.2668
13	PASUMALAI	10.8547
14	IND BHARATH	11.1962
15	KODIAYAR_60	10.7029
16	KODAIYAR_40	11.6761
17	MELAKALLOOR	11.7073
18	PAPANASAM HY	11.8207
19	SERVALAR HY	11.8062
20	OTHULUKKARPATTI	10.6049
21	KAYATHAR	11.7881
22	ANUPPANKULAM_110kV	10.5867
23	VIKRAMASINGAPURAM	10.8681
24	MELAKALLOOR_BIOMASS	11.609
25	AMBASAMUTHUR	11.2841
26	THALAYUTHU_T1	10.1116
27	THALAYUTHU_T2	10.4046
28	KADAYAM_TOFF	10.4951

4.4.2 Weak buses in the system

The fault levels without WTGs are computed and weak buses are identified if fault current is less than 5 p.u and the weak buses are tabulated in Table 4.2.

Table 4.2 Fault level less than 5 p.u

Bus No	Bus Name	Fault Level (p.u)
48	UDANGUDI_110/11 kV	4.5518
62	SANKARANKOVIL_TOFF	3.9552
80	KADAYANALLOR_110/11 kV	4.7205
81	PULIYANGUDI_110/11 kV	4.545
82	NARAYANAPURAM_110/11 kV	4.7205
84	PERUMALPATTI_110/11kV SS	4.9615
124	KARIVALAMVANTHANALLUR_110/11kVSS	4.2895

The buses which are having fault current level between 5 p.u to 9 p.u are tabulated in Appendix- C.

4.5 Summary

Short circuit study is conducted for the Tirunelveli network. Weak and strong points are identified. It is suggested that weak points are prone to power evacuation problem in case of increasing wind power penetration.

5. POWER FLOW WITH TCSC AND VSC BASED HVDC SYSTEM

5.1 Introduction to TCSC

The FACTS technology is an attractive option for increasing system operation flexibility. The recent developments in high-current, high-power electronic devices are making it possible to control the power flows on the high voltage side of the network during both steady state and transient operation. One important FACTS controller is the Thyristor Controlled Series Compensator (TCSC), which allows rapid and continuous changes of the transmission line impedance. Active power flows along the compensated transmission line can be maintained at a specified value under a range of operating conditions.

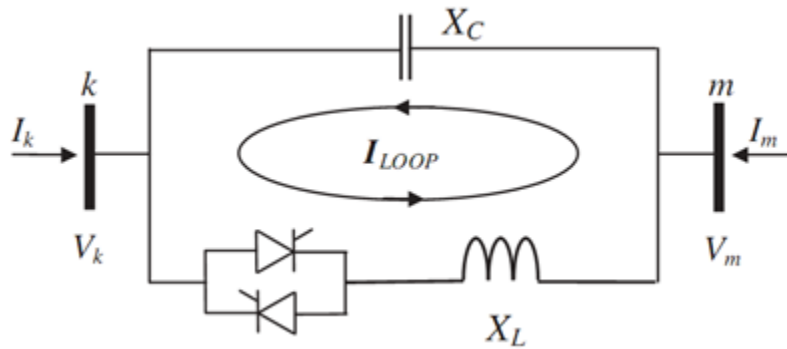


Figure 5.1.TCSC Model.

Figure.5.1 is a schematic representation of a TCSC module [Z], which consists of a series capacitor bank, in parallel with a Thyristor Controlled Reactor (TCR). The controlling element is the thyristor controller, shown as a bi-directional thyristor valve. In power flow studies, the TCSC can be represented in several forms such as the model presented is based on the concept of a variable series compensator, whose reactance is adjusted in order to constrain the power flow across the branch to a specified value. The changing reactance represents the fundamental frequency equivalent reactance of the TCSC module. The linearized TCSC power flow equations, with respect to the firing angle, are incorporated into Newton-Raphson power flow algorithm. The TCSC firing angle is combined with the nodal voltage magnitudes and angles inside the Jacobian matrix leading to very robust iterative power flow solution.

The main and basic objective of TCSC in power system is to enhance power flow and improve system stability. The deployment of TCSC in transmission line also improves subsynchronous resonance (SSR) mitigation, Power Oscillation Damping (POD) and Transient Stability (TS). In this project, the TCSC is used for power evacuation of the large scale wind farm installed capacity of around 3000 MW in Tirunelveli region.

5.2 TCSC Fundamental impedance

The voltages and currents in the TCSC circuit under the full range operating conditions is given as,

$$\mathbf{Z}_{TCSC} = \mathbf{R}_{TCSC} + j \mathbf{X}_{TCSC} = \mathbf{V}_{TCSC} / \mathbf{I}_{line} \quad 5.1$$

where (bold type indicates complex quantities). $\mathbf{V}_{TCSC}$ is the fundamental frequency voltage across the TCSC module, $\mathbf{I}_{line}$ is the fundamental frequency line current and $\mathbf{Z}_{TCSC}$ is the TCSC impedance. The voltage $\mathbf{V}_{TCSC}$ is equal to the voltage across the TCSC capacitor and equation (5.1) can be written as,

$$\mathbf{V}_{TCSC} = -j \mathbf{X}_{TCSC} * \mathbf{I}_{line} \quad 5.2$$

If the external power network is represented by an idealized current source, as seen from the TCSC terminals, this current source is equal to the sum of the currents flowing through the TCSC capacitor and inductor.

The TCSC reactance can then be expressed as,

$$\mathbf{X}_{TCSC} = -j \mathbf{X}_C (\mathbf{I}_{line} - \mathbf{I}_{TCR}) / \mathbf{I}_{line} \quad 5.3$$

Substituting the expression for $\mathbf{I}_{TCR}$ and assuming $\mathbf{I}_{line} = I \cos wt$, leads to the fundamental frequency TCSC equivalent reactance, as a function of the TCSC firing angle, α

$$\mathbf{X}_{TCSC} = -\mathbf{X}_{LC} + C_1 \{2(\pi - \alpha) + \sin 2(\pi - \alpha)\} - C_2 \cos^2(\pi - \alpha) (\omega \tan(\omega(\pi - \alpha)) - \tan(\pi - \alpha)) \quad 5.4$$

where $\omega = 2\pi f$

$$\mathbf{X}_{LC} = \frac{\mathbf{X}_C \mathbf{X}_L}{\mathbf{X}_C - \mathbf{X}_L} \quad 5.5$$

$$C_1 = \frac{X_C + X_{LC}}{\pi} \quad 5.6$$

$$C_2 = \frac{4X_{LC}^2}{X_L \pi} \quad 5.7$$

$$X_L = \omega L ; X_C = 1 / \omega C$$

The overall TCSC fundamental reactance is given as

$$X_{TCR||C} = (X_L * X_C) / (X_L - X_C) / \pi \{2(\pi - \alpha) + \sin(2\alpha)\} \quad 5.8$$

5.3 TCSC Power flow model

The admittance matrix of the TCSC module shown in Figure 5.1 can be given as,

$$\begin{bmatrix} I_k \\ I_m \end{bmatrix} = \begin{bmatrix} jB_{kk} & jB_{km} \\ jB_{mk} & jB_{mm} \end{bmatrix} \begin{bmatrix} V_k \\ V_m \end{bmatrix} \quad 5.9$$

where, $B_{kk} = B_{mm} = B_{TCSC} = -1/X_{TCSC}$

$$B_{km} = B_{mk} = B_{TCSC} = -1/X_{TCSC} \quad 5.10$$

The TCSC power equations at node k are

$$P_k = -V_k V_m B_{TCSC} \sin(\Theta_k - \Theta_m) \quad 5.11$$

$$Q_k = V_k^2 B_{TCSC} + V_k V_m B_{TCSC} \cos(\Theta_k - \Theta_m) \quad 5.12$$

The TCSC linearized power equations with respect to the firing angle are,

$$\frac{\partial P_k}{\partial \alpha} = P_k B_{TCSC(1)} \frac{\partial X_{TCSC(t)}}{\partial \alpha} \quad 5.13$$

$$\frac{\partial Q_k}{\partial \alpha} = Q_k B_{TCSC(1)} \frac{\partial X_{TCSC(1)}}{\partial \alpha} \quad 5.14$$

$$\frac{\partial B_{TCSC(1)}}{\partial \alpha} = B_{TCSC(1)}^2 \frac{\partial X_{TCSC(1)}}{\partial \alpha} \quad 5.15$$

$$\begin{aligned} \frac{\partial X_{TCSC(1)}}{\partial \alpha} = & -2C_1(1 + \cos(2\alpha)) \\ & + C_2 \sin(2\alpha)(\varpi \tan(\varpi(x - \alpha)) - \tan \alpha) \\ & + C_2 \left(\varpi^2 \frac{\cos^2(\pi - \alpha)}{\cos^2(\varpi(\pi - \alpha))} - 1 \right) \end{aligned}$$

For node m exchange the subscripts k as m in (5.11)-(5.14).

When the TCSC module is controlling the active power flowing from nodes k to m , at a specified value, the set of linearized power flow equations is give as,

$$\begin{bmatrix} \Delta P_k \\ \Delta P_m \\ \Delta Q_k \\ \Delta Q_m \\ \Delta P_{km} \end{bmatrix}^i = \begin{bmatrix} \frac{\partial P_k}{\partial \theta_k} & \frac{\partial P_k}{\partial \theta_m} & \frac{\partial P_k}{\partial V_k} V_k & \frac{\partial P_k}{\partial V_m} V_m & \frac{\partial P_k}{\partial \alpha} \\ \frac{\partial P_m}{\partial \theta_k} & \frac{\partial P_m}{\partial \theta_m} & \frac{\partial P_m}{\partial V_k} V_k & \frac{\partial P_m}{\partial V_m} V_m & \frac{\partial P_m}{\partial \alpha} \\ \frac{\partial Q_k}{\partial \theta_k} & \frac{\partial Q_k}{\partial \theta_m} & \frac{\partial Q_k}{\partial V_k} V_k & \frac{\partial Q_k}{\partial V_m} V_m & \frac{\partial Q_k}{\partial \alpha} \\ \frac{\partial Q_m}{\partial \theta_k} & \frac{\partial Q_m}{\partial \theta_m} & \frac{\partial Q_m}{\partial V_k} V_k & \frac{\partial Q_m}{\partial V_m} V_m & \frac{\partial Q_m}{\partial \alpha} \\ \frac{\partial P_{km}^\alpha}{\partial \theta_k} & \frac{\partial P_{km}^\alpha}{\partial \theta_m} & \frac{\partial P_{km}^\alpha}{\partial V_k} V_k & \frac{\partial P_{km}^\alpha}{\partial V_m} V_m & \frac{\partial P_{km}^\alpha}{\partial \alpha} \end{bmatrix}^i \begin{bmatrix} \Delta \theta_k \\ \Delta \theta_m \\ \Delta V_k \\ \Delta V_m \\ \Delta \alpha \end{bmatrix}$$

Where superscript i indicates iteration, $\Delta P_{km} = P_{km}^{\alpha, \text{reg}} - P_{km}^\alpha$ is the active power flow mismatch for the TCSC module, $\Delta \alpha = \alpha^{i+1} - \alpha$ is the incremental change in the TCSC's firing angle and $P_{km}^\alpha = P_k$.

5.3.1 TCSC Impedance as a function of firing angle

The behavior of the TCSC power flow model is influenced greatly by the number of resonant points in the TCSC impedance-firing angle characteristic, in the range of 90-180°. The number of resonant points (poles) in a TCSC module is determined by Equation (5.18).

$$\alpha = \pi \left(1 - \frac{(2n-1)\omega\sqrt{LC}}{2} \right) \quad n = 1, 2, 3 \dots \quad 5.18$$

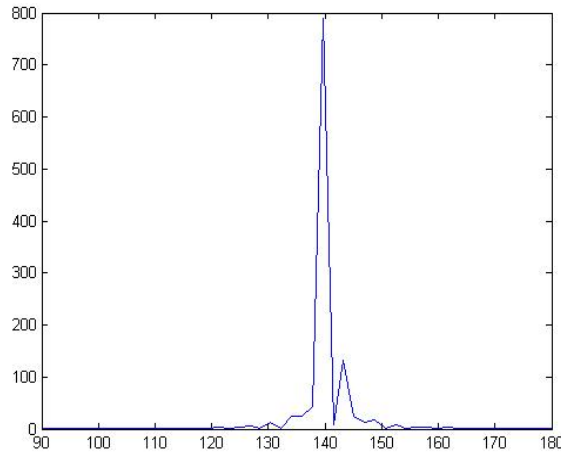


Figure 5.2 Variation of TCSC equivalent X_{TCSC} with α

Figure 5.2 shows the fundamental frequency TCSC reactance profile, as function of the firing angle. The partial derivatives of these parameters with respect to the firing angle are also shown in these figures. As shown in Figure. 5.2, a resonant point exists at $\alpha = 141.81^\circ$. This pole defines the transition from the inductive to the capacitive regions. It should be noted that near the resonant point, small variations of the firing angle will induce large changes in both X_{TCSC} and $dX_{TCSC} / d\alpha$. This, in turn, may lead to ill conditioned TCSC power equations and Jacobian terms.

5.3.2 Firing angle initial condition

The initial conditions are often responsible for Newton-Raphson power flow solution diverging or arriving at some anomalous value. In order to avoid ill conditioned Jacobians, if the customary zero voltage angle initialization is used, then TCSC is represented as a fixed reactance in the first iteration. In subsequent iterations, a small voltage angle difference at the TCSC

terminals takes place and the firing angle TCSC model is used. The initial condition for the TCSC's firing angle is selected within the range of $\pm 8^\circ$ from the resonant point.

5.3.3 Truncated adjustments

When solving network with TCSC, large mismatch values in ΔP , ΔQ , and ΔP_{km} , may take place in the early stages of the iterative process resulting in poor convergence. The problem is aggravated if the level of compensation required maintains a specified active power flow is near to a resonant point. In this case, large increments in the TCSC firing angle produce changes from the capacitive to the inductive regions and vice versa, causing the solution process to oscillate. In order to reduce unwanted numerical problems, the computed adjustments are replaced by truncated adjustments, if they exceed a specified limit. The size of correction in the firing angle adjustment has been limited during the backward substitution to 5° . The truncated adjustment effect is propagated throughout the remaining of the backward substitution.

5.3.4 Limits revision

The power mismatch equations are used to activate limits revision in all the controllable elements. The TCSC revision criterion is based on its active power mismatch equation,

$$\Delta P_{km}^{\alpha} = P_{km}^{\alpha, reg} + P_{km}^{\alpha} \quad 5.19$$

The limit revision is activated when equation (5.19) satisfies a predefined tolerance. If a limit violation takes place then the firing angle is fixed at that limit and the regulated active power flow is freed. In this situation no further attempts are made to control this active power for the remaining of the iterative process.

5.4 VSC based HVDC Transmission for wind power evacuation

5.4.1 VSC based HVDC Transmission

Voltage Source Converter based HVDC link has emerged as the latest state of art technology in medium power transmission. The developments in symmetrical turn off capability devices, especially IGBT and PWM control technique has led to this technology. Voltage Source Converter (VSC) based HVDC converters use IGBT valves with gate turn-on and turn-off capabilities eliminating the chances for commutation failure. Power flow reversal can be made easily by current reversal. Pulse Width Modulation (PWM) control enables independent control of real and reactive power in all the four quadrants. The region of control in all the quadrants is limited by the device characteristics.

5.4.2 Why VSC based HVDC transmission for wind power evacuation?

VSC-HVDC which is also called “HVDC Light” is proposed to be promising backbone for distributed and renewable generation systems, such as wind farms. Grid connection via VSC-HVDC system enables wind farms to smooth their impact on the grid stability and power quality. Trend for renewable energy makes VSC-HVDC an essential technology for the grid-connection of wind farms because wind farms are lightly populated and therefore the weakest part of a state’s electricity grid. VSC- HVDC link can feed weak ac bus and also evacuate power from the weak ac systems. It also provides fast and decoupled active and reactive power control. VSC based HVDC links are extensively used for integrating large onshore/offshore wind farms with grid, used in city infeed, integration of remote small scale generations and deep sea crossings.

It offers high level of flexibility of power flow control in medium power transmission level (upto 350MW). The voltage rating of VSC based HVDC link is limited to ± 300 kV due to the constraints imposed by IGBT ratings. It can also be used for supplying power to a passive grid as there are no constraints imposed by short circuit ratio. Control coordination of VSC based HVDC link is also easy, because there is no need for communication link.

It can also enhance the damping and improve the stability when a suitable additional damping controller is employed. If the dc capacitance value changes, the dc voltage at the converter end varies accordingly. By controlling the dc capacitor voltage power balance is attained in the

system. VSC is similar to synchronous source without inertia and controls active power and reactive power almost independently.

5.4.3 World wide VSC installations for wind power evacuation

The first commercial High Voltage Direct Current (HVDC) was installed to power the Island of Gotland from shore by a 96 km 100 kV subsea cable in 1955. The first commercial voltage source converter (VSC) HVDC was introduced in 1997 on the island of Gotland. This has been followed by several VSC-HVDC projects around the world. Since then ratings and applications has progressed rapidly. The world wide installation of VSC-based HVDC projects are tabulated in Table5.1.

Table 5.1 World wide installations of VSC-HVDC projects and basic parameters.

Project Name	Year of Commission	Power rating	Number of circuits	AC voltage	DC voltage	Length of DC cables	Comments and reasons for choosing VSC-HVDC	Topology	Semi-convertors
Hellsjön, Sweden	1997	3 MW ±3 MVar	1	10 kV (both ends)	± 10 kV	10 km Overhead lines	Test transmission. Synchronous AC grid.	2-level	IGBTs (series connected)
Gotland HVDC Light, Sweden	1999	50 MW -55 to +50 MVar	1	80 kV (both ends)	± 80 kV	2 × 70 km Submarine cables	Wind power (voltage support). Easy to get permission for underground cables.	2-level	IGBTs (series connected)
Eagle Pass, USA	2000	36MW ±36 MVar	1	138 kV (both sides)	± 15.9 kV	Back-to-back HVDC Light station	Controlled asynchronous connection for trading. Voltage control. Power exchange.	3-level NPC	IGBTs (series connected)
Tjæreborg, Denmark	2000	8 MVA 7.2 MW -3 to +4 MVar	1	10.5 kV (both sides)	± 9 kV	2 × 4.3 km Submarine	Wind power. Demonstration project. Normally synchronous AC grid with variable frequency control.	2-level	IGBTs (series connected)
Terrenora Interconnection (Directlink), Australia	2000	180 MW -165 to +90 MVar	3	110 kV – Bungalora 132 kV – Mullumbimby	± 80 kV	6 × 59 km Underground cable	Energy trade. Asynchronous AC grid. Easy to get permission for underground cables.	2-level	IGBTs (series connected)
MurrayLink, Australia	2002	220 MW -150 to +140 MVar	1	132 kV – Berri 220 kV – Red Cliffs	± 150 kV	2 × 180 km Underground cable	Controlled asynchronous connection for trading. Easy to get permission for underground cables.	3-level ANPC	IGBTs (series connected)
CrossSound, USA	2002	330 MW ±150 MVar	1	345 kV – New-Heaven 138 kV – Shoreham	± 150 kV	2 × 40 km Submarine cables	Controlled synchronous connection for power exchange. Submarine cables.	3-level ANPC	IGBTs (series connected)
Troll A offshore, Norway	2005	84 MW -20 to +24 MVar	2	132 kV – Kollsnes 56 kV - Troll	± 60 kV	4 × 70 km Submarine cables	Environment, CO ₂ tax. Long submarine cable distance. Compactness of converter on platform electrification.	2-level	IGBTs (series connected)
Estlink, Estonia-Finland	2006	350 MW ±125 MVar	1	330 kV – Estonia 400 kV – Finland	± 150 kV	2 × 31 km Underground 2 × 74 km Submarine	Length of land cable, sea crossing and non-synchronous AC systems.	2-level	IGBTs (series connected)
NORD E.ON 1, Germany	2009	400 MW	1	380 kV – Diele 170 kV – Borkum 2	± 150 kV	2 × 75 km Underground 2 × 128 km Submarine	Offshore wind farm to shore. Length of land and sea cables. Asynchronous system.	-----	IGBTs (series connected)
Caprivi Link, Namibia	2009	300 MW	1	330 kV – Zambezi 400 kV – Gerus	350 kV	970 km Overhead lines	Synchronous AC grids. Long distance, weak networks	-----	IGBTs (series connected)
Valhall offshore, Norway	2009	78 MW	1	300 kV – Lista 11 kV – Valhall	150 kV	292 km Submarine coaxial cable	Reduce cost and improve operation efficiency of the field. Minimize emission of green house gases.	2-level	IGBTs (series connected)

5.4.4 Modeling of VSC based HVDC link for power flow studies

The PWM switching control makes VSC possible to have a simultaneous adjustment of the amplitude and phase angle of the converter ac output voltage with constant dc voltage. This control characteristic allows to represent the converter's ac output voltage at a node 'k' by a modulated ac voltage source $V_{VR} \angle \delta_{VR}$, with amplitude and phase angle limits $V_{VR}^{min} \leq V_{VR} \leq V_{VR}^{max}$ and $0 \leq \delta_{VR} \leq 2\pi$, respectively. Hence, the VSC-HVDC transmission link can be represented by the voltage source-based model given in Figure. 5.3. The coupling transformer's impedance is given by Z_{VR} . The converter's dc side is represented by the active power exchanged among the converters via the common dc link, which must be balanced at any instant, and the ac-dc side voltage converter relationships.

The ac side voltage magnitude of the converter connected at node k, V_{VR} , is related to the PWM's amplitude modulation index M_{CK} , and to the average dc capacitor voltage V_{DC} as

$$V_{VR} \angle \delta_{VR} = M_{ck} K V_{dc} \quad 5.20$$

where M_{ck} – Modulation index $\in [0,1]$

If, $M_{ck} < 1$ (under modulation) ; $M_{ck} > 1$ (over modulation)

K- Transformation coefficient.

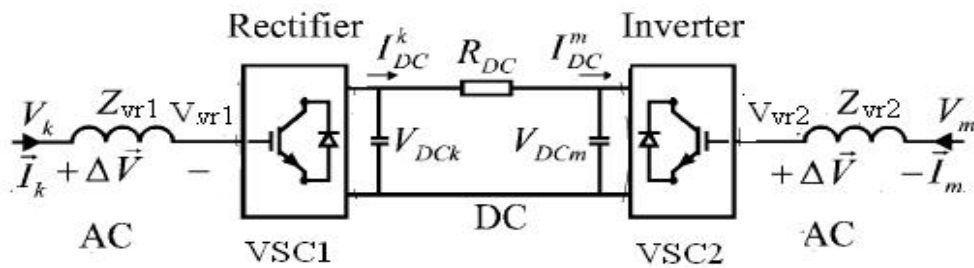


Figure 5.3 VSC-HVDC transmission link.

The power flow equations based on the equivalent circuit shown in Figure. 5.4, it is possible to obtain the power flows across the VSC-HVDC system ac terminals k and m. The powers flowing from node i to j are

$$P_{ij}^{inj} = V_i^2 G_{VRi} - V_k V_{VRi} [G_{VR} \cos(\theta_i - \delta_{VRi}) + B_{VRi} \sin(\theta_i - \delta_{VRi})] \quad 5.21$$

$$Q_{ij}^{inj} = -V_i^2 B_{VRi} - V_i V_{VRi} [G_{VRi} \sin(\theta_i - \delta_{VRi}) + B_{VRi} \cos(\theta_i - \delta_{VRi})] \quad 5.22$$

$$\text{where,} \quad Y_{VR} = 1/Z_{VR} \quad 5.23$$

$$Y_{VR} = G_{VR} + jB_{VR} \quad 5.24$$

Z_{VR} - Impedence of converter transformer

Y_{VR} - Admittance of converter transformer

V_k - AC voltage at bus k

θ_k - Voltage angle at bus k

$\bar{V}_{VR}$ - Voltage at fictitious bus

δ_{VR} - Voltage angle of fictitious bus

The power flow into the converter connected at node $i=k,m$ are given as follows

$$P_{VRi} = V_{VRi}^2 G_{VRi} - V_{VRi} V_i [G_{VRi} \cos(\delta_{VRi} - \theta_i) + B_{VRi} \sin(\delta_{VRi} - \theta_i)] \quad 5.25$$

$$Q_{VRi} = -V_{VRi}^2 B_{VRi} - V_{VRi} V_i [G_{VRi} \sin(\delta_{VRi} - \theta_i) - B_{VRi} \cos(\delta_{VRi} - \theta_i)] \quad 5.26$$

The equation relating to the active power exchanged between converters is obtained by neglecting losses in the converter circuits.

For a DC link with a series resistance R_{DC} is given by,

$$\text{Re}[V_{VRk} I_{VRk}^* + V_{VRm} I_{VRm}^*] + P_{DC}^{loss} = 0 \quad 5.27$$

where

$$P_{DC}^{loss} = (P_{VRj}^2 R_{DC}) / (V_{DCj}^{spec})^2 \quad 5.28$$

The active power-flow direction through the dc link must be in accordance with the dc voltage magnitudes. This relation is achieved by including the Kirchhoff voltage law equation on the dc side given by (5.10), where the power flowing into the converter is considered as negative.

$$\Sigma V_{DC} = V_{DCj} - V_{DCi} + P_{VRj} R_{DC} / V_{DCj} = 0 \quad 5.29$$

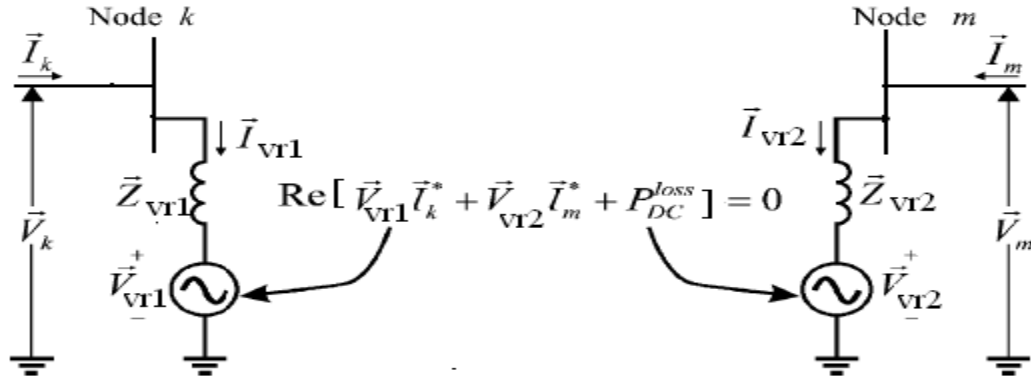


Figure 5.4 Equivalent circuit of VSC

5.4.5 Control modes

The active power exchanged between the converter and the network is controlled by adjusting the phase shift angle $\Delta\theta_i$ between the voltage on the ac bus and the fundamental frequency voltage generated by the converter,

$$\Delta\theta_i = \theta_i - \delta_{VRi} \quad 5.30$$

The reactive power flow is determined by controlling the difference between these voltage amplitudes,

$$\Delta V_{VRi} = V_i - V_{VRi} \quad 5.31$$

Hence, two independent power control loops can be used for regulation, namely active power and reactive power control loops. In the active power control loop, one converter is set to control the injected active power P_{ij}^{inj} at its ac terminal while the other is set to control the dc side voltage V_{DCj} . In the reactive power control loop, both converters have independent control over either voltage magnitude V_i or injected reactive power Q_{ij}^{inj} at their ac terminal.

Mode 1: PQ control mode

If the active and reactive powers are set to be controlled by converter i at values P_{ij}^{spec} and Q_{ij}^{spec} respectively, then the constraint equations to be satisfied are:

$$P_{ij}^{inj} - P_{ij}^{spec} = 0 \quad 5.32$$

$$Q_{ij}^{inj} - Q_{ij}^{spec} = 0 \quad 5.33$$

Mode 2: PV control mode

If the active power and ac voltage magnitude are set to be controlled by converter i, at values P_{ij}^{spec} and V_i^{spec} respectively, The constraint equations to be satisfied are

$$P_{ij}^{inj} - P_{ij}^{spec} = 0 \quad 5.34$$

$$V_i - V_i^{spec} = 0 \quad 5.35$$

In both cases, the other converter is set to control the dc side voltage, independently of the reactive power loop control setting. Since the dc side voltage is kept constant by converter at a value V_{DCj}^{spec} , this control action is used in the constraining equation representing the active power balance between the two converters to assess losses in the common dc link. Hence, the active power losses in the dc link are given by (5.9).

5.5 Incorporation of VSC based HVDC in power flow analysis

In the power flow analysis, both converters are set to provide PQ control. Then the residual equations are given by,

$$\Delta R(1) = P_{spec} - P_{HVDC1} \quad 5.36$$

$$\Delta R(2) = Q_{spec} - Q_{HVDC1} \quad 5.37$$

$$\Delta R(3) = P_{spec} - P_{HVDC2} \quad 5.38$$

$$\Delta R(4) = Q_{spec} - Q_{HVDC2} \quad 5.39$$

where

P_{spec} - Specified real power flow at HVDC terminal

Q_{spec} - Specified reactive power flow at HVDC terminal

P_{HVDC1} - Calculated real power flow at converter 1.

P_{HVDC2} - Calculated real power flow at converter 2.

Q_{HVDC1} - Calculated reactive power flow at converter 1.

Q_{HVDC2} - Calculated reactive power flow at converter 2.

The state variables for this power flow are the fictitious bus voltage magnitude and phase angle, as PQ control mode is chosen. State variables ($V_{VR1}, \delta_{VR1}, V_{VR2}, \delta_{VR2}$).

5.6 VSC MTDC system

In literature, Multiterminal VSC based DC links, embedded on existing ac network is suggested as an ideal solution for power evacuation from renewable energy sources.

Sequential power flow analysis for VSC-MTDC system with explicit representation of dc grid is presented. The flow from ac bus to dc bus is considered as drawl in ac bus and injection in dc bus and vice versa. The dc voltages at all the buses other than dc slack bus and the dc slack bus power are obtained as result of power flow solution. The Q estimate, i.e the power flow from ac bus into fictitious VSC ac bus is calculated at the end of each iteration and updated. The fictitious ac bus voltage and angle is obtained iteratively by formulating a power balance equation.

This power balance equation is formulated by equating ac bus power to dc power with losses incorporated. A generalized converter loss model where the losses linearly and quadratically depend on current flowing through the reactor is included. The VSC parameters such fictitious VSC ac bus voltage phase shift angle α , fictitious bus voltage magnitude, dc slack bus power are included as the state variable in this power flow analysis.

Power flow of dc grid is performed by the basic nodal method. MTDC network is represented as injection/drawls of power in the power flow analysis as shown in Figure.5.7 A node in the VSC MTDC network is shown in the Figure.5.6. The voltage at nodes i and j in

Figure.5.6 are denoted by V_i and V_j respectively. The admittance between the nodes i and j is denoted by Y_{dcij} .

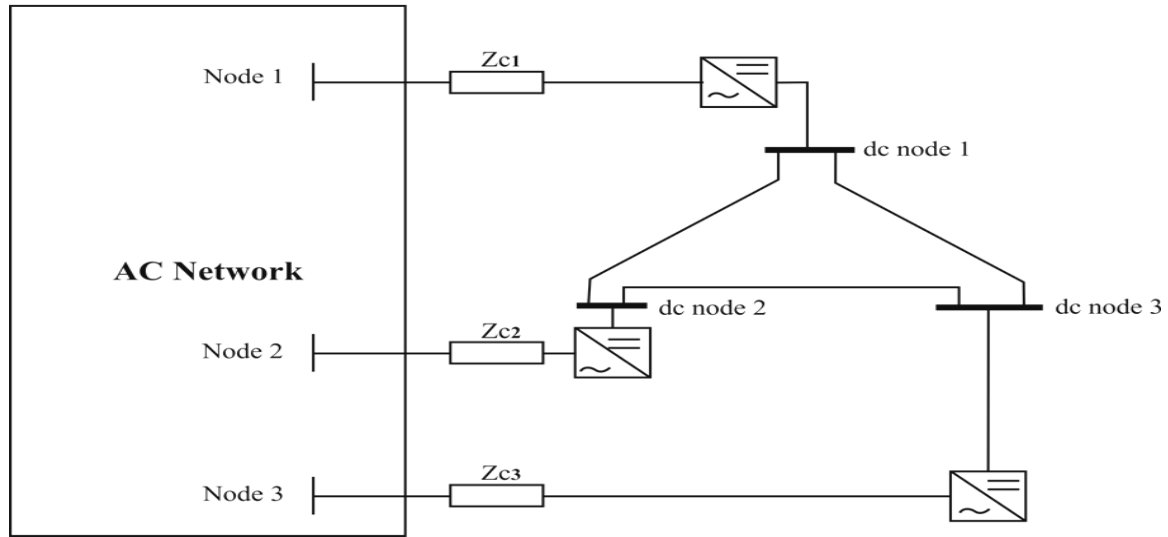


Figure. 5.5 DC network embedded on an ac network

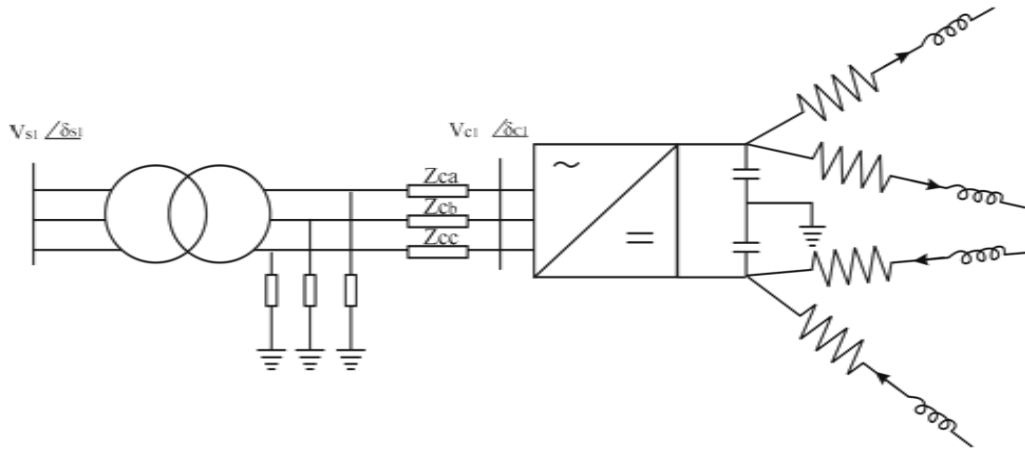


Figure.5.6 A node in a dc network

Assuming n number of nodes in the network, the injected current I_{dc_i} must be equal to the sum of the currents flowing to the other $n-1$ nodes,

$$I_{dc_i} = \sum_{j=1, j \neq i}^n Y_{dcij} (V_{dc_i} - V_{dc_j}) \quad (5.40)$$

Combining the current injections in all the nodes

$$I_{dc} = Y_{dc} V_{dc} \quad (5.41)$$

The power injection or drawl at all the buses other then dc slack bus is taken to be known prior. This is justified from the basic capability of VSC-HVDC link that link powers can be fixed and the PWM controllers adjusts the phase shift angle to track the power unless the limits are hit. Strongest bus in the multiterminal link is taken to be the slack bus. The voltage magnitude of the slack bus is freed and for all the other buses flat voltage start may be assumed.

For bipolar operation, the active power injected in the i_{th} node is given by

$$P_{dci} = 2 V_{dci} I_{dci} \quad (5.42)$$

The current injection is not known prior to dc power flow solution. DC mismatch equation is formed by equating (5.40) and (5.42).

$$I_{dci} - \frac{P_{dci}}{2V_{dci}} = 0 \quad (5.43)$$

The vector of state variables is given by

$$X = \begin{bmatrix} P_{dc_slack} \\ V_{dc_2} \\ \cdot \\ \cdot \\ V_{dc_n} \end{bmatrix} \quad (5.44)$$

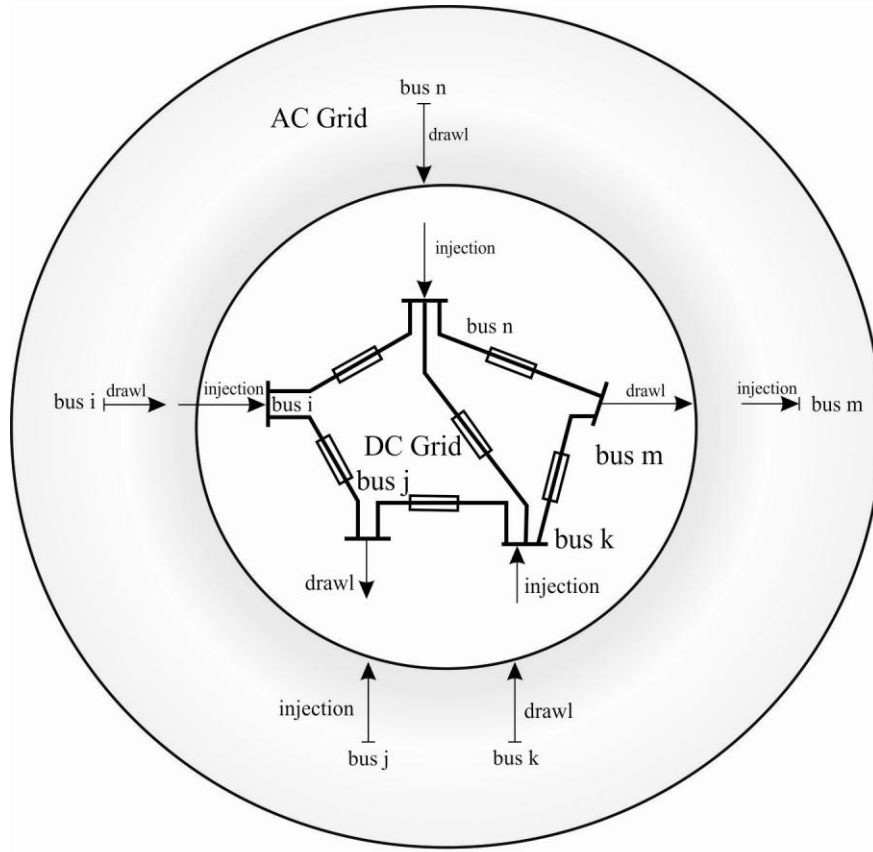


Figure. 5.7 VSC MTDC network embedded on an ac network

Thus with flat dc voltage start and the power injection/drawl at all the dc buses except the dc slack bus as known parameters the dc slack bus power and dc voltages are obtained by simple Newton-Raphson method.

5.6.1 Mathematical model of VSC MTDC link

All the dc buses are P controlled bus except the dc slack bus which takes into account of losses in the dc link and the converters. The scheduled power injection (or power drawl) from a dc bus is thus known prior. This scheduling is done based on the parallel ac lines overloading and the rating of XLPE cables. The dc ring is embedded in the existing ac network as shown in Figure. 5.7. The ac buses are connected to the voltage source converters through a coupling transformer reactance. The coupling transformer impedance is given by Z_c , where $Z_c = 1/(G_c + jB_c)$. Thus the converters are modeled as controlled voltage sources behind fictitious transformer impedances as shown in the Figure 5.8

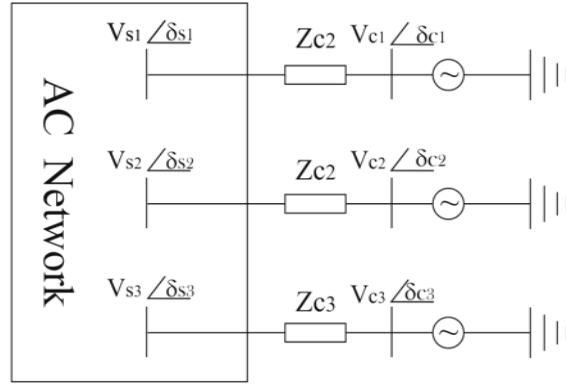


Figure.5.8 VSC station modeled as fictitious voltage source behind transformer impedance

The power flow from ac bus to converter terminal is

$$P_s = -V_s^2 G_c + V_s V_c (G_c \cos(\delta_s - \delta_c) + B_c \sin(\delta_s - \delta_c)) \quad (5.45)$$

$$Q_s = V_s^2 B_c + V_s V_c (G_c \sin(\delta_s - \delta_c) - B_c \cos(\delta_s - \delta_c)) \quad (5.46)$$

The power flow from converter terminal to ac bus is

$$P_c = V_c^2 G_c - V_s V_c (G_c \cos(\delta_s - \delta_c) - B_c \sin(\delta_s - \delta_c)) \quad (5.47)$$

$$Q_c = -V_c^2 B_c + V_s V_c (G_c \sin(\delta_s - \delta_c) + B_c \cos(\delta_s - \delta_c)) \quad (5.48)$$

with $V_s = V_s \angle \delta_s$ and $V_c = V_c \angle \delta_c$, the ac grid side and converter ac side voltage phasors respectively.

The effect of VSC-MTDC network embedded with the ac network is included as either power injection or drawl in the ac network as given in equation (5.49)

$$P_i^{sch} = P_i^g - P_i^d \pm P_i^{inj} \quad (5.49)$$

The real power balance equation is given below

$$\Delta P_i = P_i^{sch} - P_i^{cal} \quad (5.50)$$

The real power injections at all dc buses are specified except dc slack bus. The slack bus power is initialized for the first iteration and estimated subsequently. The internal dc load flow solution gives the dc slack bus power for subsequent iterations.

The reactive power flow from the ac buses to fictitious ac buses are estimated at the end of every ac iteration as it is not known prior. The reactive power balance equation is given below

$$\Delta Q_i = Q_i^{sch} - Q_i^{cal} \quad (5.51)$$

$$Q_i^{sch} = Q_i^g - Q_i^d \pm Q_i^{inj_est} \quad (5.52)$$

5.6.2 Fictitious ac bus power flow iterations

The VSC's are PWM controlled and thus can control the voltage magnitude, V_c and voltage angle, δ_c of the converter ac bus almost independently. The voltage magnitude and voltage angle of the fictitious ac bus are iteratively adjusted to satisfy the power balance equations. The P and Q mismatch equations (5.53) and (5.54) are formulated with losses incorporated.

$$\Delta P_c = P_{sch_dc} - P_c(V_c \delta_c) - P_{losses} \quad (5.53)$$

Losses in the converter transformer, phase reactor and filter are taken into account using transformer impedance Z_c . Converter losses are also estimated as per the loss model given in[11] and included in mismatch equation (5.53)

$$\Delta Q_c = Q_{inj_est} - Q_c(V_c \delta_c) \quad (5.54)$$

The 2 x 2 Jacobian matrix (18) is formulated for every converter bus and solved sequentially.

$$\begin{bmatrix} \frac{\partial P_c}{\partial \delta_c} & \frac{\partial P_c}{\partial V_c} \\ \frac{\partial Q_c}{\partial \delta_c} & \frac{\partial Q_c}{\partial V_c} \end{bmatrix} \begin{bmatrix} \Delta \delta_c \\ \Delta V_c \end{bmatrix} = \begin{bmatrix} \Delta P_c \\ \Delta Q_c \end{bmatrix} \quad (5.55)$$

The equations (5.46) and (5.47) modified by substituting $V_c \angle \alpha = k_c V_{dc} M_c \angle \alpha$ and are given as follows.

$$P_c = (k_c V_{dc} M_c)^2 G_c - V_s k_c V_{dc} M_c (G_c \cos(\delta_s - \delta_c) - B_c \sin(\delta_s - \delta_c)) \quad (5.56)$$

$$Q_s = -(k_c V_{dc} M_c)^2 B_c + V_s k_c V_{dc} M_c (G_c \sin(\delta_s - \delta_c) + B_c \cos(\delta_s - \delta_c)) \quad (5.57)$$

Its worth mentioning that $\alpha = \delta_c$. The mismatch equations (5.53) and (5.54). The 2 x 2 Jacobian matrix (5.58) is formulated for every converter bus and solved sequentially.

$$\begin{bmatrix} \frac{\partial P_c}{\partial \alpha} & \frac{\partial P_c}{\partial V_{dc}} \\ \frac{\partial Q_c}{\partial \alpha} & \frac{\partial Q_c}{\partial V_{dc}} \end{bmatrix} \begin{bmatrix} \Delta \alpha \\ \Delta V_{dc} \end{bmatrix} = \begin{bmatrix} \Delta P_c \\ \Delta Q_s \end{bmatrix} \quad (5.58)$$

5.7 Power flow analysis with TCSC

A MATLAB program has been written for the TCSC firing angle-dependent model to incorporate in our power flow program. The program has been applied to the solution of power networks of different sizes. The Tirunelveli test system consists of 156 buses, 187 transmission lines, 2860 installed wind generators and 22 transformers. This network has enough complexity to show the robustness of the TCSC model towards the convergence.

Mechanically switched series capacitors are used to compensate the line. A Static Var Compensator (SVC) is installed at node 31 to regulate voltage magnitude. This line is of slightly different design. For the purpose of this project, the mechanically switched series capacitors are replaced by TCSC's and used to control active power flow. The TCSC's are set to control the active power flow through transmission line. The TCSC electric parameters are those given in Table 5.2. The power mismatch tolerance was set at 10^{-8} . The firing angle of TCSC is initialized at 140° and convergence was obtained in five iterations.

Table 5.2 shows the maximum absolute power mismatch, firing angle and the fundamental frequency TCSC equivalent impedance at node 31. These values are given in degrees and p.u. respectively. In order to validate these results, the same case was simulated with the variable series compensator model and convergence was obtained in 5 iterations. It should be noted that when this model is used, the firing angles are calculated after the power flow has converged by resorting to an additional iterative process.

Table 5.2 Power mismatch and TCSC parameter value

Iterations	ΔP_{L1}	α degree	$X_{TCSC \text{ p.u}}$
0	5.4	150.00	-0.0183
1	0.406	150.00	-0.0183
2	1.012	146.82	-0.0298
3	0.084	148.00	-0.0232
4	0.00001	148.04	-0.0237
5	0.00000001	148.04	-0.0237

TCSC is carefully designed to exhibit a single resonant point. However, changes in the original parameters may take place due to the ageing of capacitors. It is not unlikely that TCSC's may exhibit more than one resonant point. This has provided the motivation for analyzing the behavior of the power flow algorithm when solving systems that contain TCSC's with more than one resonant point. When the fundamental frequency TCSC reactance presents multiple resonance points, different values of firing angle give the compensation levels required to achieve a specific active power flow.

5.7.1 Power flow with 80% wind power penetration (without TCSC)

For 80% of installed capacity of wind generation and with 64-shunt capacitors. It is observed that 110kV -17 Transmission lines are overloaded (>100%) and 230/110 kV -2 transformers are overloaded.

5.7.2 Power flow with 80% wind power penetration (with TCSC)

A single module TCSC is installed in one of the circuit in 400kV double circuit between Abisekapatty to Chekkanoorani. The Figure 5.9 shows the TCSC Module of Abisekapatty to Chekkanoorani. The TCSC module is provided with 27 % fixed compensation and 8% to 20 % of variable compensation.

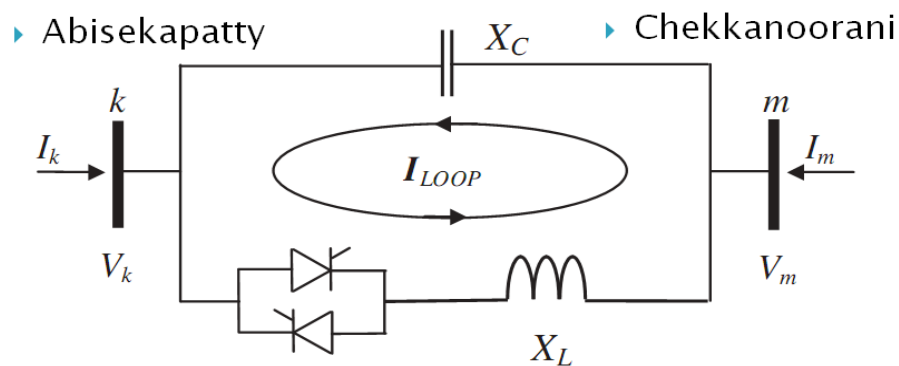


Figure 5.9 TCSC Module of Abisekapatty to Chekkanoorani

The Table 5.3 shows the power flow comparison with / without TCSC considering 80% wind power generation.

Table 5.3 Comparison of power flow results

S.No	Quantity	Without TCSC	With TCSC	Comments
1	Real power Transferred	225.51 MW	307.5 MW	81.99 MW power flow is enhanced

5.7.3 Installed TCSC projects in India

Table 5.4 –TCSC projects-Data1

TCSC Projects	K		$\omega = \sqrt{X_c/X_l}$	Reasonance region in Degree	Boost Factor
	FSC	TCSC			
Kanpur-Ballabgarh	27%	8-20%	2.7452	$147^\circ - 147.5^\circ$	1:2.5
Rourkela-Raipur	40%	5-15%	2.5007	$143.5^\circ - 144^\circ$	1:3
Purnea-Gorakhpur	40%	5-15%	-	-	1:3

Table 5.5 –TCSC projects-Data2

TCSC Projects	Capacitive operating range in Ω	Capacitive operating range in deg.	Max.Power Transfer in pu	
			With FSC	With FSC+TCSC
Kanpur-Ballabgarh	10.40-26.12	180°-151.15°	1.370	1.506-1.621
Rourkela-Raipur	6.81-20.81	180°-148°	1.667	1.791-1.884

5.8 Power flow analysis with VSC-HVDC

5.8.1 Results from power flow analysis (Lines overloaded >100%)

The Table 5.6 tabulates the results obtained by power flow with VSC based HVDC.

Table 5.6 Results from power flow analysis (lines overloading >100%)

Sl No	From Bus	To Bus	Percentage of Overloading (%)
1	CHEKKA42	SIPCOT2	112.7807
2	SRPUDU21	ARALVOIM	102.8457
3	RADHAPUR	KOTTAIKA	111.0518
4	VEERASEG	UTHUMALA	108.8940
5	RAJAPALA	RAJTOFF2	100.0837
6	SRPUDU21	MUPPTOFF	110.2754
7	SRPUDU21	PERUTOFF	109.5918

8	PALATOFF	KARUNKUL	108.1888
9	MUPPTOFF	PERUNGUD	119.6111
10	KAYATR21	AYYANARO	146.7240
11	KOTTAIKA	SATHANK	133.7107
12	KEELAVEE	KAYATR21	133.9105
13	VADDAKKA	SANKAN21	104.3723
14	KOODATOF	SANKAN21	107.9203
15	SURULIYA	RAJTOFF2	105.7389

The transmission line1 (Kayathar21-Ayyanaroothu) has to transfer $1.3924+0.5570j$ p.u of power from Ayyanaroothu to Kayathar21. The line is loaded 176.22% for this operation. The overloading transmission line can be replaced by either VSC based HVDC link, or by providing addition 110 KV line with existing line, in order to reduce the loading of the transmission line.

The DC link has to carry the real power which is transmitted when the line is an AC link. The line taken for the HVDC link is Copper conductor in air. The maximum power that can be handled by this type is 312.95 MW. A detail of other types of conductors is given in Appendix. The different loading levels, if the overloading line is replaced with DC link or double circuited are given in Table 5.7.

Table 5.7 Comparison between double circuit AC link Vs VSC-HVDC

Sl.no	From	To	Percentage of loading (%) (with dc link)	Percentage of loading (%) (with double circuit ac line)
1	Kayathar21	Ayyanaroothu	44.5	88.11
2	KottaiKarunkulam	Sathankulam	37.6	66.24
3	Sattur	O.Thulukkarpathy	38.7	66.64
4	Veerasegamani	Uthumalai	27.33	59.34
5	Anuppankulam	Sattur_Toff	34.15	59.67
6	S.R Pudur	Aralvaimozhi	29.22	69.78

As the overloading line is upgraded, the power handling capacity of that line increases. For example the transmission line between Kayathar to Ayyanaroothu is loaded to 176.22% for the given loading condition. If it is replaced with HVDC link, the loading of the line reduces to 44.5% and for double circuited line, the value is 88.11%. From the above results, it is inferred that the transmission lines can be loaded further till its maximum capacity.

5.9 VSC MTDC System power flow results

A dc ring is formulated as shown in the Figure 5.8 to relieve the overloading in four lines.

Bus n- S R Pudur ; Bus m –Aralvaimozhi ; Bus k- Muppantal Toff ;

Bus j-Perungudi ; Bus i-Perungudi Toff

The AC power generated from all the wind farms are converted into DC and fed into the DC grid at Muppantal Toff, Aralvaimozhi, Perungudi and Perungudi-Toff. It is inverted at SR Pudur and the inverter is connected to the existing AC grid. The additional wind farms, if installed can be connected to the DC grid. VSC-MTDC is cost effective compared to two terminal VSC links.

Table 5.8 Flow in the AC lines with DC ring embedded

Lines	MW	MVAR	Percentage loading(%)
Aralvaimozhi to SR Pudur	54.61	-32.35	70.52
Muppanthal to Aralvaimozhi	49.36	-19.06	58.79
Muppanthal to MuppanToff	31.93	-7.41	36.42
Perungudi to MuppanToff	71.99	-27.81	85.76
Perunkudi to PeruToff	23.86	-8.29	28.06
PeruToff to SRPudur	65.41	-27.67	78.91
MuppanToff to SRPudur	68.27	-27.61	81.81

Table 5.9 Flows in DC ring

Lines	MW
Aralvaimozhi to SR Pudur	74.35
MuppanthalToff to Aralvaimozhi	40.06
Perungudi to MuppanToff	50.6
Perunkudi to PeruToff	59.94
PeruToff to SRPudur	60.09

5.10 Summary

A TCSC power flow model has been presented. The TCR's firing angle is taken as state variable, which is regulated in order to obtain the level of compensation required to achieve a specified active power flow. The test system has been taken for the power evacuation study. If the transmission line is long (>250 km) then we can go for the Thyristor Controlled Series Compensator (TCSC) for power flow enhancement. This Series compensation (Thyristor Controlled Series Compensator) avoids the overloading of transmission lines for 60% to 90% of wind power penetration. TCSC can enhance the power around 310 MW for transmission line between Abisekapatti to Chekkanoorani. But the line length is 162km so it comes under medium transmission line. Hence a dedicated 400 kV transmission corridor from Chekkanoorani to the load centre (>250 kms) may be proposed with TCSC installation.

Two terminal VSC HVDC link and VSC-MTDC models have been presented. A dc ring is proposed to relieve the four overloaded lines. The power flow analysis reveals that the burden can be taken by the dc ring embedded on the ac network. Thus capacity addition can be done along the dc ring and overloading of the ac lines can be avoided.

6. TRANSIENT STABILITY ANALYSIS

6.1 Introduction

The power supply and power demand in the system must always be satisfied and be in equilibrium conditions during normal and dynamic changes in the system. Particularly during pre and post dynamic events, the system voltage, frequency and equipment loadings shall be within normal limits ensuring quality of power supply and acceptability of system operation.

- The operating limits of the equipments shall remain within normal operating limits or shall quickly return to normal limits following dynamic events. These dynamic events can be large disturbances following which the system should be able to continue and service the loads without loss of quality, loss of load. The response of the system to large disturbances and its ability to return to normal operating conditions is generally termed transient stability or large signal performance of the system.
- The heterogeneous system of synchronous machines and their controllers together with load and other system dynamic characteristics shall be stable, so that the system can transit from one operating condition to another without sustained oscillations limiting power transfers. This is generally referred to as small signal stability.
- The load characteristics and the power supply characteristics of the system shall be in tune with each other so that the load voltages are always healthy without any significant low voltage problems and its consequences which may lead to loss of system load and service. This problem is generally termed voltage stability problem

6.1.1 Classification of power system stability

The Figure 6.1 gives the detailed classification of power system stability [1]

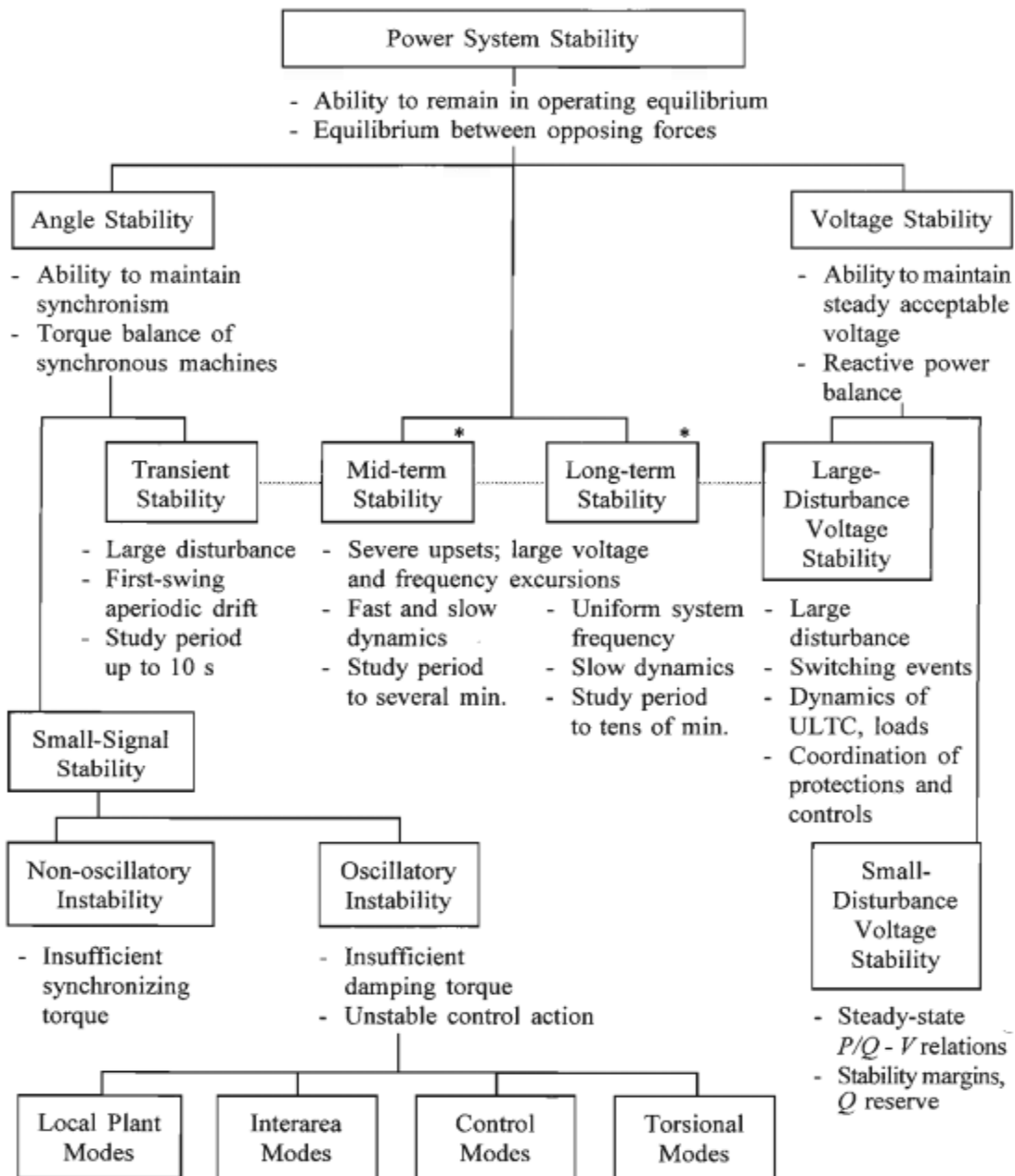


Figure 6.1 Classification of power system stability

*With availability of improved analytical techniques providing unified approach for analysis of fast and slow dynamics, distinction between mid-term and long-term stability has become less significant

6.2 Transient stability analysis

The recovery of a power system subjected to a severe large disturbance is of interest to system planners and operators. Typically the system must be designed and operated in such a way that a specified number of credible contingencies do not result in failure of quality and continuity of power supply to the loads. This calls for accurate calculation of the system dynamic behaviour, which includes the electro-mechanical dynamic characteristics of the rotating machines, generator controls, static var compensators, loads, protective systems and other controls. Transient stability analysis can be used for dynamic analysis over time periods from few seconds to few minutes depending on the time constants of the dynamic phenomenon modeled.

6.3 Modelling of power system components for stability studies

Synchronous generators form the principal source of electrical energy in power system. Therefore an accurate modelling of their dynamic performance is of fundamental importance for the study of power system stability. The synchronous generators are modelled as classical machines. Similarly the modelling of wind turbine and induction generators is of prime importance. The induction generators modelled in this section are of squirrel cage type and the analysis may be extended to Doubly Fed Induction Generators (DFIG) as a future scope.

6.3.1 Synchronous machine model

The synchronous generators are modelled as classical machines with rotor angle (δ) and speed (ω) as state variables.

$$J \frac{d\omega}{dt} = T_m - T_e \quad 6.1$$

$$\frac{d\delta}{dt} = \omega - \omega_s \quad 6.2$$

The equivalent circuit for classical model of the generator is given in Figure 6.2.a. This equivalent circuit is in Thevenin's form [3], and the Norton form of the equivalent circuit is shown in Figure 6.1.b.

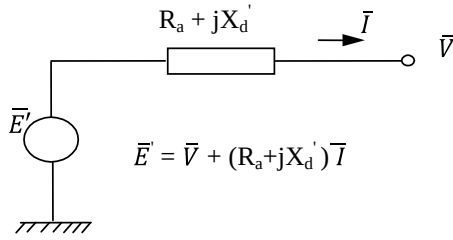


Figure 6.2 (a) Thevenin

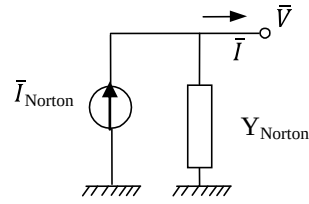


Figure 6.2 (b) Norton

Figure 6.2 Generators representation for network solution

where,

X_d' - Direct axis transient reactance

I_{Norton} - Norton current source.

The expressions for the current source and the admittance are given by

$$\bar{I}_{Norton} = E' \angle \delta / (R_a + jX_d') \quad 6.3$$

$$Y_{Norton} = 1 / (R_a + jX_d') \quad 6.4$$

The Norton admittance and it gets added to the diagonal of bus admittance matrix $\mathbf{Y}$ corresponding to the node where the generator is connected.

6.3.2 Transmission line model

The transmission lines are modeled as π -circuits using positive sequence parameters: series resistance, series reactance and half-line charging.

6.3.3 Load model

The loads are modelled as constant admittances. The admittances are computed from the initial load flow solution as shown below.

$$Y_L = (P_L - j Q_L) / |V_L|^2 \quad 6.5$$

Where, P_L and Q_L are the active and reactive powers of the load

$|V_L|$ is the magnitude of the voltage of the load bus computed by load flow analysis

Y_L is the load admittance and it gets added to the diagonal of bus admittance matrix $\mathbf{Y}$

corresponding to the node where the load is connected.

6.3.4 Wind turbine model

The simple aerodynamic model commonly used to represent the turbine is based on the power coefficient, C_p versus the tip speed ratio, λ . The torque and power extracted from the wind turbine are given by,

$$T_m = \frac{P_m}{\omega_r} \quad 6.6$$

$$P_m = \frac{1}{2} \rho A u_w^3 C_p \quad 6.7$$

Where, P_m - power extracted from the wind turbine, ρ - density of air, A - swept area of the blades, C_p - power coefficient, u_w - wind speed.

The tip speed ratio is given by

$$\lambda = \frac{\omega R}{u_w} \quad 6.8$$

Where, ω - Rotor speed of the wind turbine (low shaft speed)

R – Radius of the wind turbine rotor

The general functional representation of C_p is

$$C_p(\lambda, \theta) = C_1 \left(\frac{C_2}{\Lambda} - C_3 \theta - C_4 \theta^x - C_5 \right) e^{\frac{-C_6}{\Lambda}} \quad 6.9$$

Where,
$$\frac{1}{\Lambda} = \frac{1}{\lambda + 0.08\theta} - \frac{0.035}{1 - \theta^3}$$

θ -pitch angle and C_1 to C_6 and x are constants.

6.3.5 Induction generator model

The induction generator can be represented by the well-known equivalent circuit shown in Figure 6.3.a

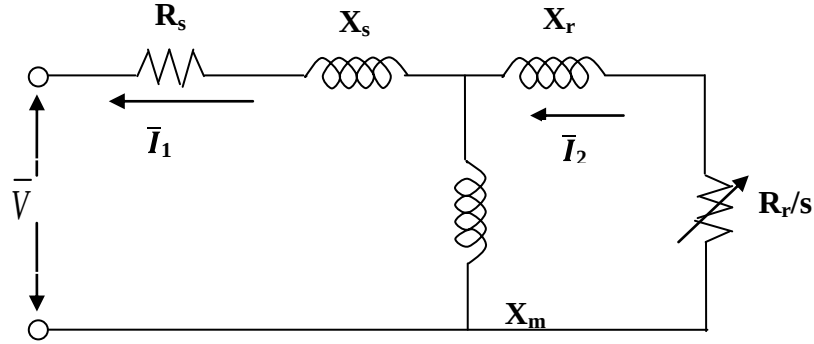


Figure 6.3.a Steady state equivalent circuit of induction generator

R_s -Stator resistance

R_r - Rotor resistance

X_s -Stator leakage reactance

X_r - Rotor leakage reactance

X_m -Magnetizing reactance

$\bar{I}_1$ -Stator current

$\bar{I}_2$ -Rotor current

$\bar{V}$ -Terminal voltage

s -Slip given by, $(\omega_s - \omega_r)/\omega_s$

N_t -Number of wind turbine generators

From Figure 6.3.a, the current I_1 can be written as,

$$\bar{I}_1 = \frac{-\bar{V}}{(R_s + R_e) + j(X_s + X_e)} \quad 6.10$$

where,

$$R_e + jX_e = \frac{jX_m \left(\frac{R_r}{s} + jX_r \right)}{\frac{R_r}{s} + j(X_m + X_r)} \quad 6.11$$

The per-unit active power transferred from the rotor to the stator through air gap, called air gap power, is readily calculated from the equivalent circuit as,

$$P_g = -\bar{I}_2^2 \frac{R_r}{s} \quad 6.12$$

The electrical power developed in the rotor is,

$$P_g = -\bar{I}_2^2 \frac{R_r}{s} (1 - s) \quad 6.13$$

where the slip is negative.

The electrical torque developed is then given by,

$$T_e(v, s) = \frac{-\bar{V}^2 X_m^2 \frac{R_r}{s}}{\left[\left(R_1 + \frac{R_r}{s} \right)^2 + (X_s + X_r)^2 \right] [R_1^2 + (X_1 + X_m)^2]} \quad 6.14$$

where $R_1 + jX_1 = \frac{jX_m(R_s + jX_s)}{R_s + j(X_s + X_m)}$ 6.15

The steady state equivalent for wind farm is obtained by replacing the parameters of individual wind generators as shown in the Figure 6.4.b

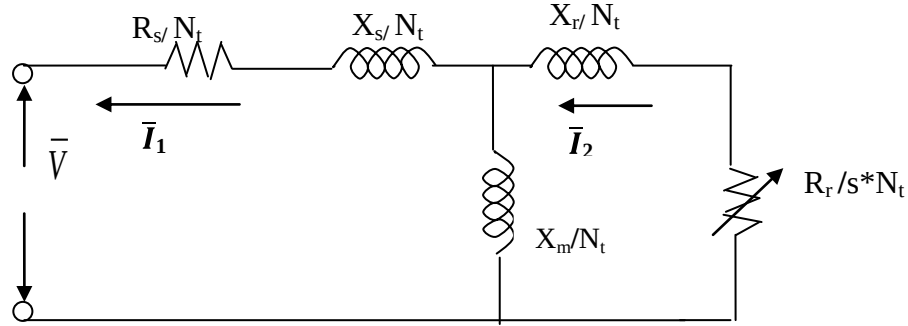


Figure 6.3.b Steady state equivalent circuit of wind farm

6.3.6 Transient model of IG

In developing the transient model of the induction machine as shown in Figure 6.4.a, it is worth noting the following aspects of its characteristics, which differ from those of the synchronous machine.

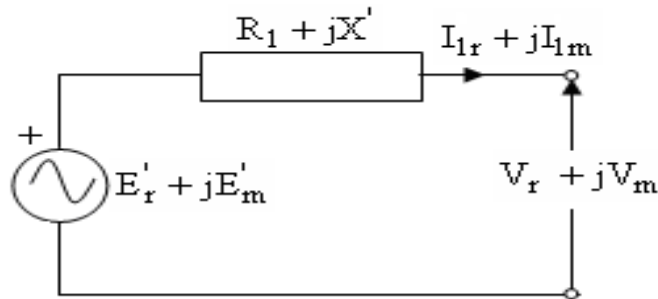


Figure 6.4.a Transient equivalent circuit of induction generator

- The rotor has symmetrical structure. This makes the d-axis and q-axis equivalent circuits identical.
- There is no excitation source applied to the rotor windings. Consequently, the dynamics of the rotor circuits are determined by slip, rather than by excitation control.
- The currents induced in the shorted rotor windings produce a field with the same number of poles as that produced by the stator winding. Rotor winding may therefore be modeled by an equivalent three-phase winding similar to the stator.
- The stator and the rotor windings are sinusoidally distributed along the air-gap as far as the mutual effect with the rotor is concerned.
- The stator slots cause no appreciable variations of the rotor inductances with rotor position.
- Magnetic hysteresis and saturation effects are negligible.

The transient state equivalent for wind farm is obtained by replacing the parameters of individual wind generators as shown in the Figure 6.4.b

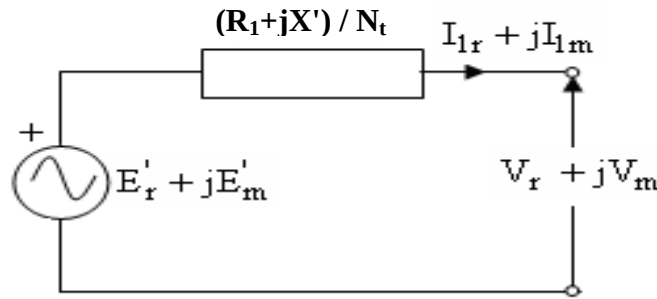


Figure 6.4.b Transient equivalent circuit of wind farm

The general expression for electrical torque is given by,

$$\bar{T}_e = E'_r I_r + E'_m I_m \quad 6.16$$

The acceleration of the driven equipment and the generator is given by

$$\frac{2H_{sys}}{(\omega_{sm}/\omega_{Bm})} \frac{\partial \bar{s}}{\partial t} = \bar{T}_m(s) - \bar{T}_e(s) \quad 6.17$$

The expression for transient voltage is expressed as differential equations can be given as

$$pE'_r = -\frac{1}{T'_0} [E'_r - (X_s - X')I_m] + s\omega_s E'_d \quad 6.18$$

$$pE'_m = -\frac{1}{T'_0} [E'_m + (X_s - X')I_r] - s\omega_s E'_r \quad 6.19$$

$$s = (\omega_s - \omega_r)/\omega_s \quad 6.20$$

where, H – Inertia constant in second, s – slip .

6.4 Initialization

Any dynamic study begins with a load flow which gives the initial snap shot of the system [3]. The system is assumed to be in steady state from $t = -\infty$ to $t=0$. From the initial load flow solution, active and reactive powers absorbed by the generators and the terminal voltage phasor will be known. Then the initialization of other quantities can be done as shown below:

1. The stator current phasor

$$\bar{I} = \frac{P-jQ}{\bar{V}^*} \quad 6.22$$

2. The state variables to be initialized for classical machines are δ and ω . In steady state, the machine speed is assumed to be synchronous speed, hence, $\omega = \omega_s$.

3. For classical machine, the rotor angle is initialized ($t=0$) as the phase angle of voltage behind transient reactance.

4. The transient voltage of synchronous generator is given as

$$\bar{E}' \angle \delta = \bar{V} + (R + jX'_d)\bar{I} \quad 6.23$$

5. The transient voltage of induction generator is given as

$$\bar{E}' = \bar{V} + (R + jX')\bar{I} \quad 6.24$$

where $E' = E'_r + jE'_m$

6. The initial value of slip is obtained from load flow. Runge-Kutta (R-K) fourth order method is employed for numerical integration technique. R-K fourth order method requires calculation of four estimates for each state variable to obtain the values at the next time step. The estimates of state variables are change in phase angles (k_1, k_2, k_3, k_4) , change in speed (l_1, l_2, l_3, l_4) , change in E'_r (x_1, x_2, x_3, x_4) , change in E'_m (y_1, y_2, y_3, y_4) and change in slip (z_1, z_2, z_3, z_4) .

6.5 Algorithm to advance simulation by one time step

The stepwise computations to be performed to advance the simulation by one step from $t - \Delta t$ to t are as follows [3]. The time step width (Δt) used in the algorithm is 0.001 sec.

Assumptions:

- The machines are considered to be classical (no controllers)
- Damping ignored
- Loads are assumed as constant admittances

Preparation:

- The initial conditions for δ , ω and voltage are obtained from load flow and the past history terms for δ and ω are obtained from the initial conditions.
- The initial condition synchronous generator and induction generator are calculated assuming that the system in steady state initially.

Note:

- The loads are converted into the constant admittances and these are pushed in to diagonal elements of the corresponding load buses.

$$Y_{\text{TRANBUS } ii} = Y_{ii} + Y_{Li} \quad \text{Here } i \text{ is for all load buses} \quad 6.25$$

- The diagonal elements of Y_{bus} corresponding to all synchronous generators are modified as:

$$Y_{\text{TRANBUS } ii} = Y_{ii} + 1/(R_i + jX'_{di}) \quad 6.26$$

iii. The diagonal elements of Y_{bus} corresponding to induction generator are modified as:

$$Y_{TRANBUS\ ii} = Y_{ii} + 1/(R_i + jX_i') \quad 6.27$$

Assume that we have completed the simulation up to the time $t-\Delta t$, and the following quantities are known at $t-\Delta t$. State variables of induction generator (E_r' , E_m' , s) and synchronous generator (δ , ω)

The computational steps to advance simulation from time $t-\Delta t$ to time t are given below.

Step 1: Compute the electrical power for synchronous machine.

$$P_e = \bar{V} \bar{I}^* \quad 6.28$$

$$\bar{I} = \frac{\bar{E}' \angle \delta - \bar{V}}{R + jX_d'} \quad 6.29$$

Step 2: The general expression for electrical torque of induction generator is given by,

$$T_e = E_r' I_r + E_m' I_m \quad 6.30$$

$$\bar{I} = \frac{E_r' + jE_m' - \bar{V}}{R + jX} \quad 6.31$$

where, $I = I_r + jI_m$

Step3: Compute first estimate of all state variables a follows

$$k_1 = \frac{d\delta}{dt} = \omega - \omega_s \quad 6.32$$

Similarly compute the first estimate for other state variables (ω , E_r' , E_m' , s) as l_1 , x_1 , y_1 , z_1

Step 4: Calculate the Norton current

For Synchronous Generator

$$\bar{I}_{Norton} = \frac{E' \angle (\delta(t) + \frac{k_1}{2})}{R + jX_d'} \quad 6.33$$

For Induction Generator

$$\bar{I}_{\text{Norton}} = \frac{(E_r' + \frac{x_1}{2}) + j(E_m' + \frac{y_1}{2})}{R + jX'} \quad 6.34$$

Step 5: Solve for network equations, $[Y][V] = [I]$

Similarly compute the second, third and fourth estimates of other state variables using Step1 to Step 4.

$$k_2 = f\left(x_i + \frac{1}{2}h, y_i + \frac{1}{2}k_1h\right)$$

$$k_3 = f\left(x_i + \frac{1}{2}h, y_i + \frac{1}{2}k_2h\right)$$

$$k_4 = f(x_i + h, y_i + k_3h)$$

Step 6: Update the state variables $(\delta, \omega, E_r', E_m', s)$ and advance the time step to $t+\Delta t$.

6.6 Handling network discontinuities

For the normal time advance and the first solution at the discontinuity, the induction generator is represented by the Norton equivalent [3]. The second solution is iterative as far as terminal voltage is concerned since slip, being a state variable, cannot change across a discontinuity. The second solution is computed using the model described by Norton equivalent.

The pre-disturbance solution at a discontinuity is called the first solution and the post disturbance solution is called the second solution.

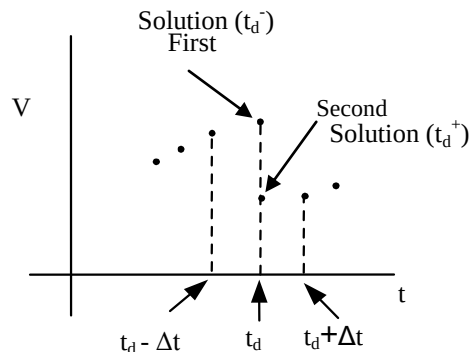


Figure 6.5 Handling network discontinuities; dots denote the points computed by the algorithm.

6.7 Effect of wind generator on transient stability

The transient stability analysis is performed for the test system by applying three phase fault at various locations of the Tirunelveli network. The transient behaviour of the wind farms is analysed without LVRT capability and with LVRT capability.

6.7.1 Low Voltage Ride Through (LVRT)

The ability of a wind turbine generator to withstand voltage variations caused by grid disturbances is referred to as LVRT-capability. Large-scale wind farms, which are connected into utility grid, can be seen as conventional large generator in terms of system operation, if they are disconnected from the grid. Thus the disconnection of the wind power farms could further aggravate the situation.

Wind power farms have more limited capability to provide voltage support during faults than synchronous generating units. Accordingly, most utility has put forward requirement to dynamic voltage recovery of wind farms during grid faults under name of low voltage ride through (LVRT) requirement in their grid codes.

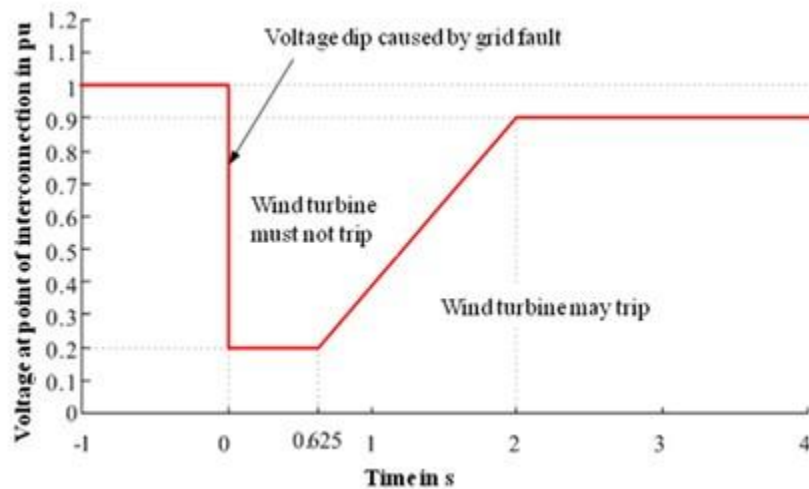


Figure 6.6 Low-Voltage Ride-Through of wind farm

LVRT is described by a voltage against time characteristic as shown in the Figure 6.6, denoting the minimum required immunity of the wind power station to dips of the system voltage. In case of dips above the residual voltage, wind farms must remain in operation, whereas they can disconnect in the event of dips below the residual limit. Transient voltage

recovery is mostly required to go back to the allowed steady state voltage drop during fault clearing time. The voltage prescribed in LVRT generally corresponds to the voltage at the grid connection point depending on the particular code requirements.

6.8 Wind farm behaviour without LVRT capability

The transient stability analysis is performed for the test system by considering wind turbine generator without LVRT capability.

6.8.1 Fault at KANYAKUMARI Bus

The Kanyakumari bus is exporting 0.2 MW power to grid which is connected to Tengampudur bus and Maharajapuram bus .When a three phase fault is applied at Kanyakumari bus at 1.0 second and cleared at 1.25 second, the variations in voltages following the disturbance are plotted in Figure 6.7.

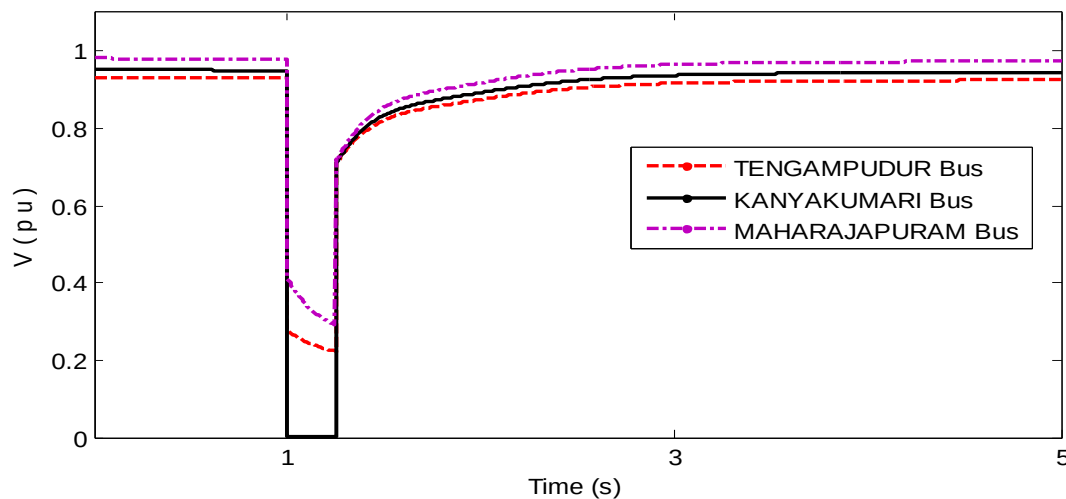


Figure 6.7 Voltage variations of Kanyakumari bus and nearer buses for three phase fault.

It is observed that fault at Kanyakumari bus has least impact on the voltages at the nearer buses. The voltage at Kanyakumari bus does not regain steady-state voltage after clearing the fault.

6.8.2 Fault at SR_PUDUR21 Bus

The SR_Pudur 21 bus is exporting 1.8 MW power to grid which is connected to Thuckalay bus and Aralvoimozhi bus .When a three phase fault is applied at SR_Pudur 21 bus at 1.0 second and cleared at 1.25 second, the variations in voltages following a disturbance are plotted in Figure 6.8.

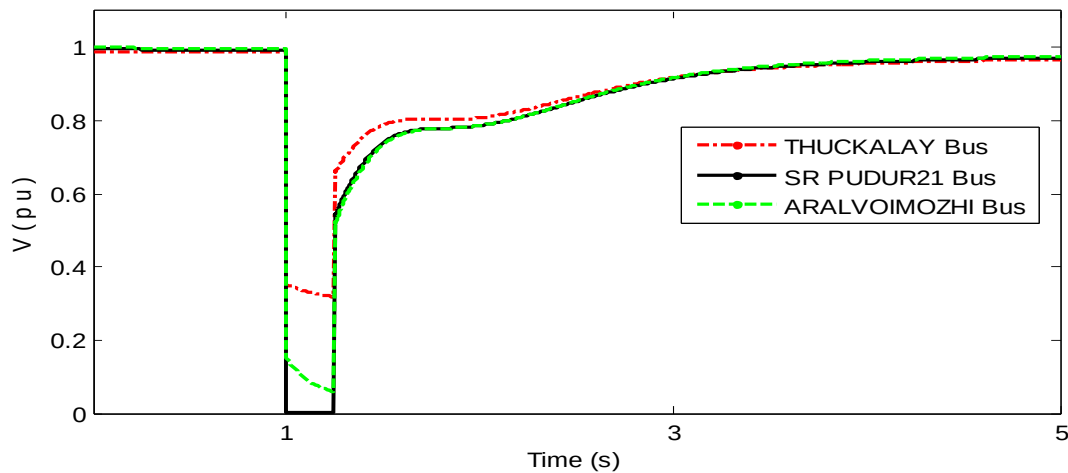


Figure6.8 Voltage variations of SR_Pudur 21 bus and nearer buses for three phase fault.

It is observed that fault at SR_Pudur 21 bus has lesser impact on the voltages at the nearer buses. The voltage at SR_Pudur 21 bus does not regain steady-state voltage after clearing the fault.

6.8.3 Fault at VEERAN21 Bus

The Veeran21 bus is exporting 161.28 MW power to grid which is connected to Veeranm2 bus. When a three phase fault is applied at Veeran21 bus at 1.0 second and cleared at 1.25 second, the variations in voltages following a disturbance are plotted in Figure 6.9.

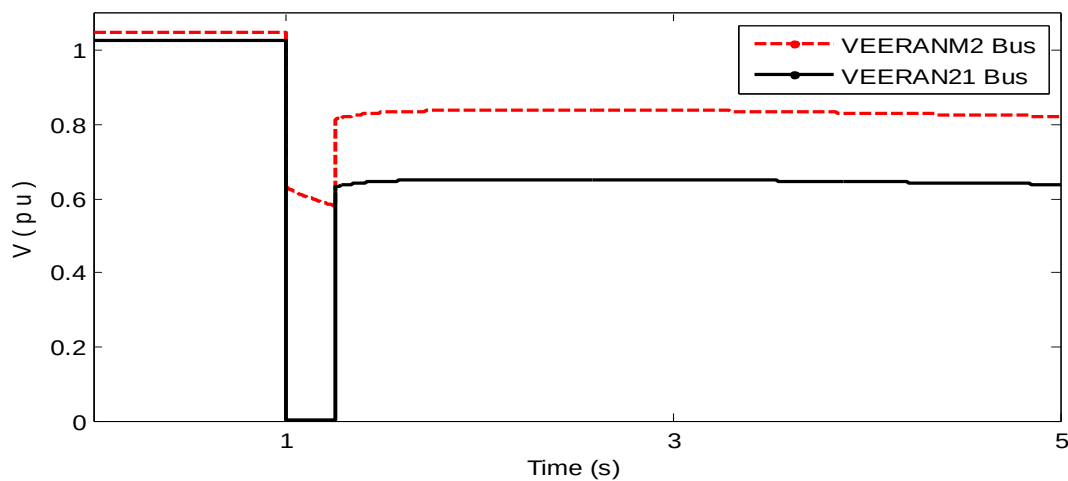


Figure6.9 Voltage variations of Veeran21 bus and nearer buses for three phase fault.

It is observed that fault at Veeran21 bus has more impact on the voltages at the nearer bus. The voltage profile at Veeran21 bus is very poor after clearing the fault.

6.8.4 Fault at AMDAPURAM Bus

The Amdapuram bus is exporting 70.8 MW power to grid which is connected to Kodikur2 bus and Chekka42 bus. When a three phase fault is applied at Amdapuram bus at 1.0 second and cleared at 1.25 second, the variations in voltages following a disturbance are plotted in Figure 6.10.

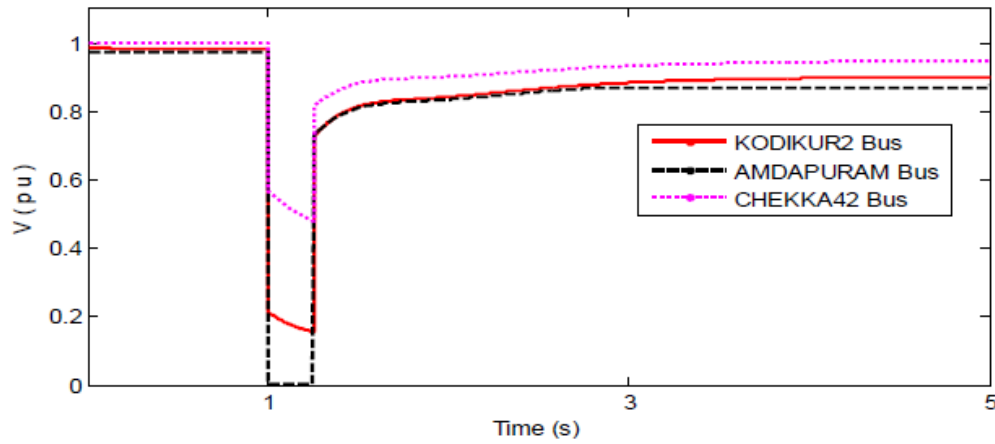


Figure 6.10 Voltage variations of Amdapuram bus and nearer buses for three phase fault.

It is observed that fault at Amdapuram bus has lesser impact on the voltages at the nearer bus. The voltage profile at Amdapuram bus does not regain to initial steady-state voltage after clearing the fault.

6.9 Wind farm behaviour with LVRT capability

The transient stability analysis is performed for the test system by considering wind turbine generator with LVRT capability.

6.9.1 Fault at KANYAKUMARI Bus

A three phase fault is applied at Kanyakumari bus at 1.0 second and cleared at 1.25 second. The variations in voltage and induction generator slip following a disturbance are plotted.

The voltage profile of Kanyakumari bus and nearby wind farm connecting buses such as Maharajapuram, SRpudur21, and Karunkulam buses are plotted in Figure 6.11.a and 6.11.b respectively.

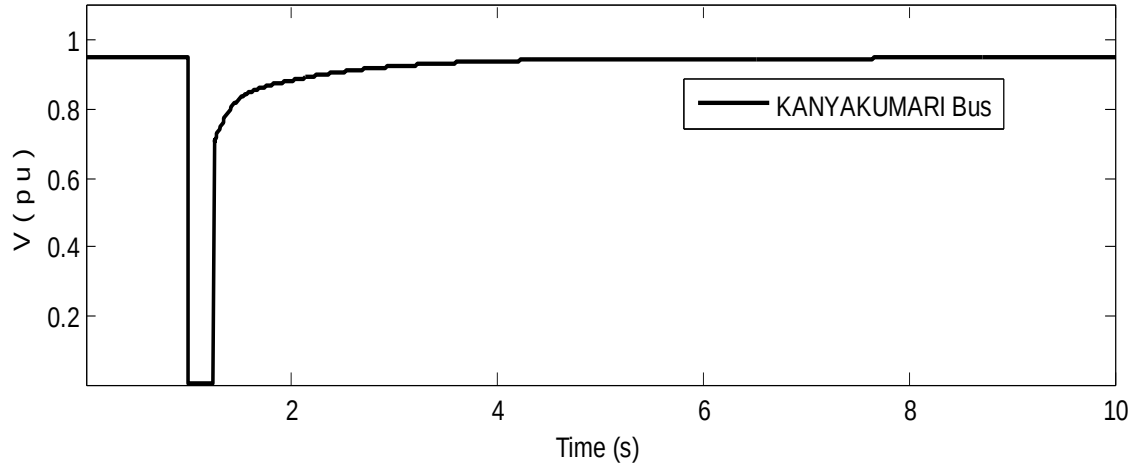


Figure 6.11.a Voltage variations at Kanyakumari bus for three phase fault

Variation of slip at Kanyakumari bus and nearer wind farm connecting bus such as Maharajapuram, SR pudur21, and Karunkulam buses are plotted in Figure 6.11.c

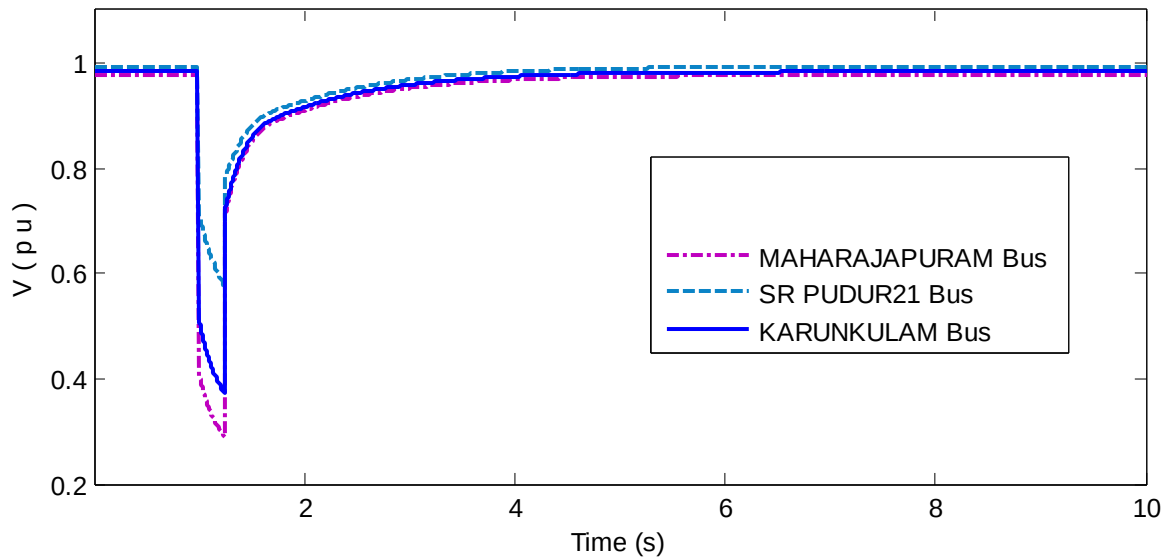


Figure 6.11.b Voltage variations of buses nearer to Kanyakumari bus for three phase fault

It is observed from Figure 6.11.a that the Kanyakumari bus voltage regains voltage to 1 p.u and reaches steady state after the removal of fault. From Figure 6.11.b it is observed that fault at Kanyakumari bus causes a sudden dip in voltage at nearby Maharajapuram bus, SR pudur21 bus and Karunkulam bus during fault and regains steady-state voltage after clearing the fault. The wind farms located at these locations have fault-ride through capability.

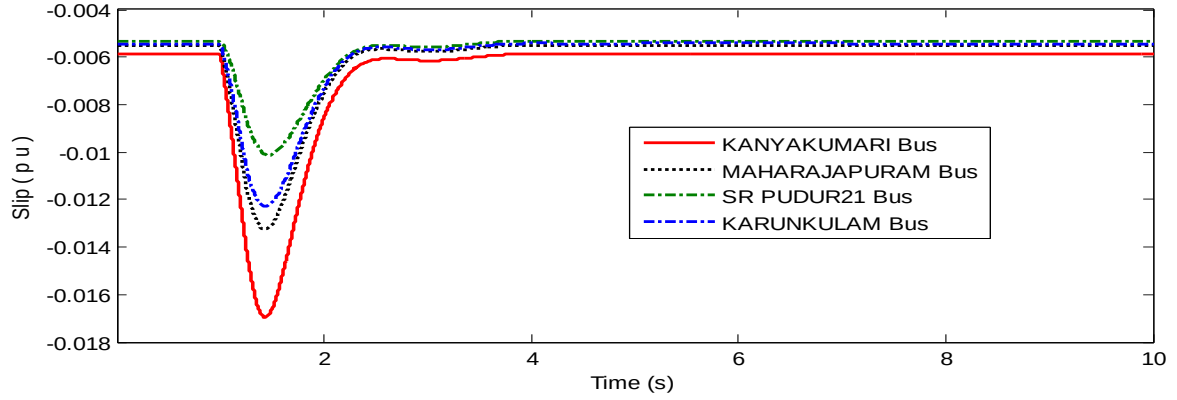


Figure6.11.c Slip variations of Kanyakumari bus and nearer buses for three phase fault.

From Figure 6.11.c it can be noted that the wind farms at Maharajapuram bus, SR pudur 21 bus, Karunkulam bus and Kanyakumari bus undergo an increase in slip in the negative direction. Slip is increasing in the negative direction means that the induction generators rotors are over speeding beyond the rated speed. But after the clearance the machines have regained their steady-state speed. Hence, the system is stable for this fault.

6.9.2 Fault at SR PUDUR21 Bus

A three phase fault is applied at SR pudur21 bus at 1.0 second and cleared at 1.25 second. The variations in voltage and induction generator slip following a disturbance are plotted.

The voltage profile of SR pudur21 bus and nearby wind farm connecting Aralvoimozhi bus is plotted in Figure6.12.a and 6.12.b respectively.

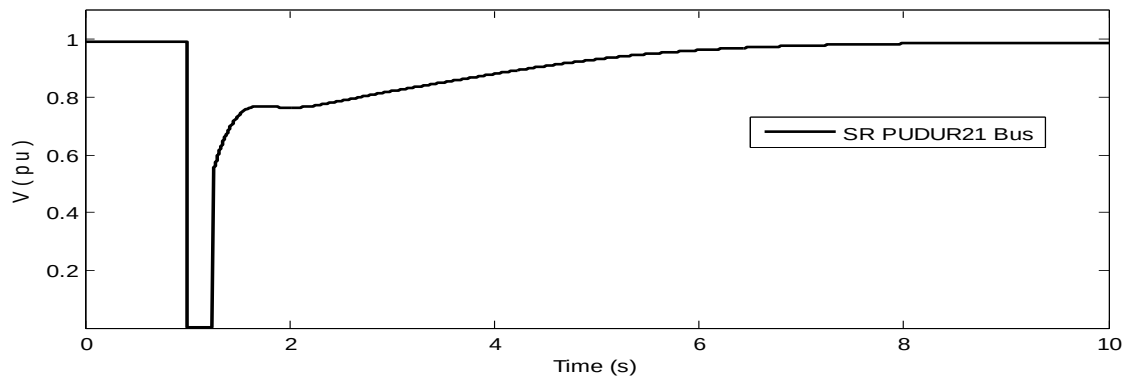


Figure6.12.a Voltage variations at SR pudur21 bus for three phase fault

The slip of SR pudur21 bus and nearer wind farm connecting Aralvoimozhi bus is plotted in Figure 6.12.c. It is observed that from Figure 6.12.a the SR pudur21 bus voltage regains to 1 p.u and reaches steady state after the removal of fault.

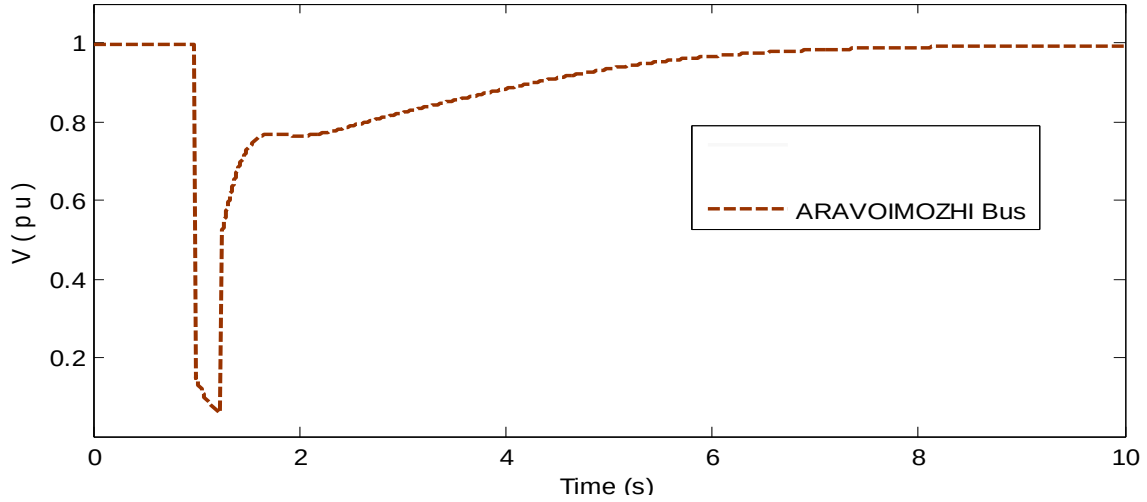


Figure 6.12.b Voltage variations at Aralvoimozhi bus for three phase fault

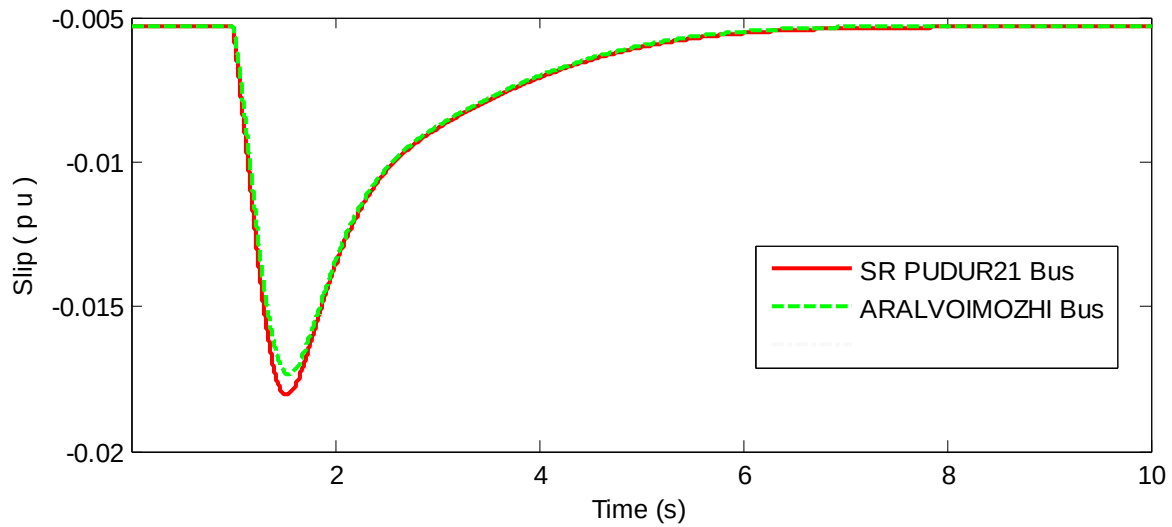


Figure 6.12.c Slip variations of SR pudur21 bus and Aralvoimozhi bus for three phase fault.

It is also observed from Figure 6.12.b that fault at SR pudur21 bus causes a sudden dip in voltage at nearby Aralvoimozhi bus during fault and regains steady-state voltage after clearing the fault. The wind farms located at these locations have fault-ride through capability.

From Figure 6.12.c it can be noted that the wind farms at SR pudur21 and Aralvoimozhi buses undergoes an increase in slip in the negative direction. Slip is increasing in the negative direction means that the induction generators rotors are over speeding beyond the rated speed. But after the clearance the machines have regained their steady-state speed. Hence, the system is stable for this fault.

6.9.3 Fault at VEERAN21 Bus

A three phase fault is applied at Veeran21 bus at 1.0 second and cleared at 1.25 second. The voltage profile of Veeran21 bus and nearby wind farm connecting buses such as Veerasegamani, Kayathar21, and Kannanalloor buses are plotted in Figure 6.13.a

The slip of Veeran21 bus and nearer wind farm connecting bus such as Veerasegamani, Kayatr 21, and Kannanalloor bus are plotted in Figure 6.13.b.

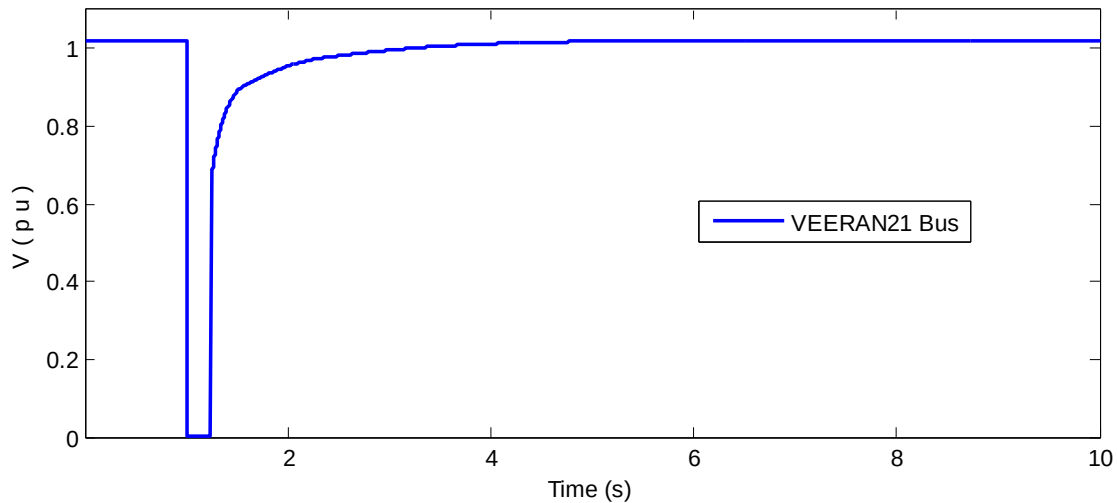


Figure 6.8.a Voltage variations at Veeran21 bus for three phase fault

It is observed that from Figure 6.13.a the Veeran21 bus voltage regains to 1 p.u and reaches steady state after the removal of fault. It is also observed Figure 6.13.b that fault at Veeran21 bus causes a sudden dip in voltage at nearby Veerasegamani, Kayatr21, and Kannanalloor buses during fault and regains steady-state voltage after clearing the fault. The wind farms located at these locations have fault-ride through capability.

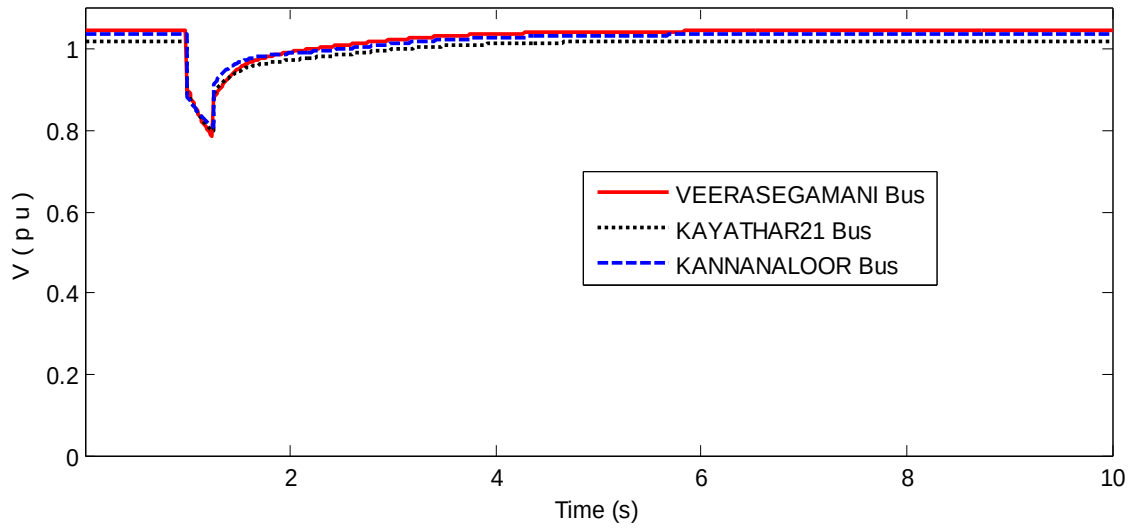


Figure 6.13.b Voltage variations of buses nearer to Veeran21 bus for three phase fault

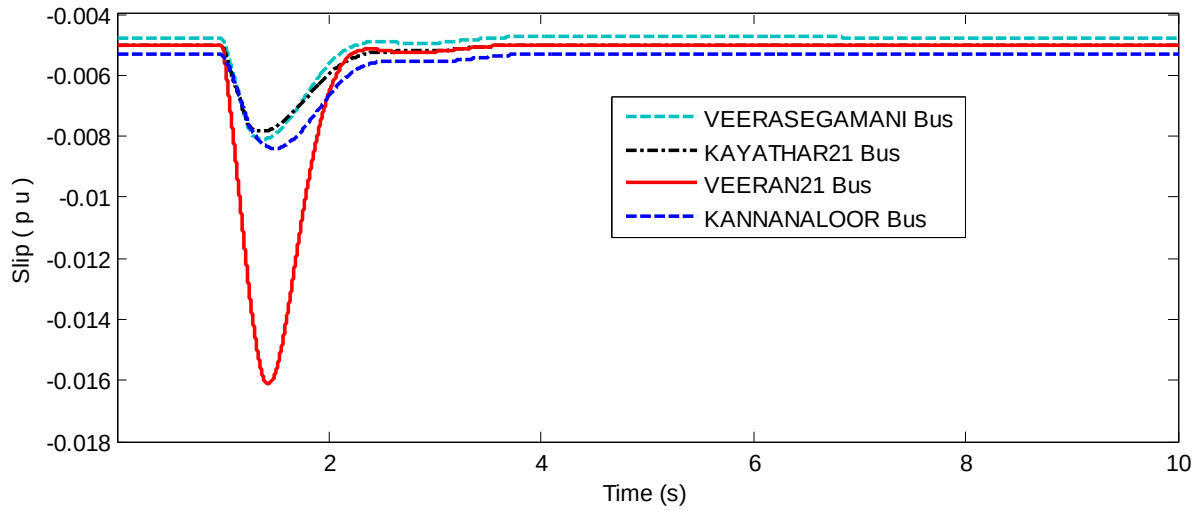


Figure 6.13.c Slip variations of Veeran21 bus and nearer buses for three phase fault.

From Figure 6.13.c it can be noted that the wind farms at Veerasesamani, Kayatr21, and Kannanalloor buses undergo an increase in slip in the negative direction. Slip is increasing in the negative direction means that the induction generators rotors are over speeding beyond the rated speed. But after the clearance the machines have regained their steady-state speed. Hence, the system is stable for this fault.

6.9.4 Fault at AMDAPURAM Bus

A three phase fault is applied at Amdapuram bus at 1.0 second and cleared at 1.25 second. The voltage profile of Amdapuram bus and nearby wind farm connecting Veerasegamani bus is plotted in Figure 6.14.a and 6.14.b respectively. The slip of Amdapuram bus and nearer wind farm connecting Veerasegamani bus are plotted in Figure 6.14.c

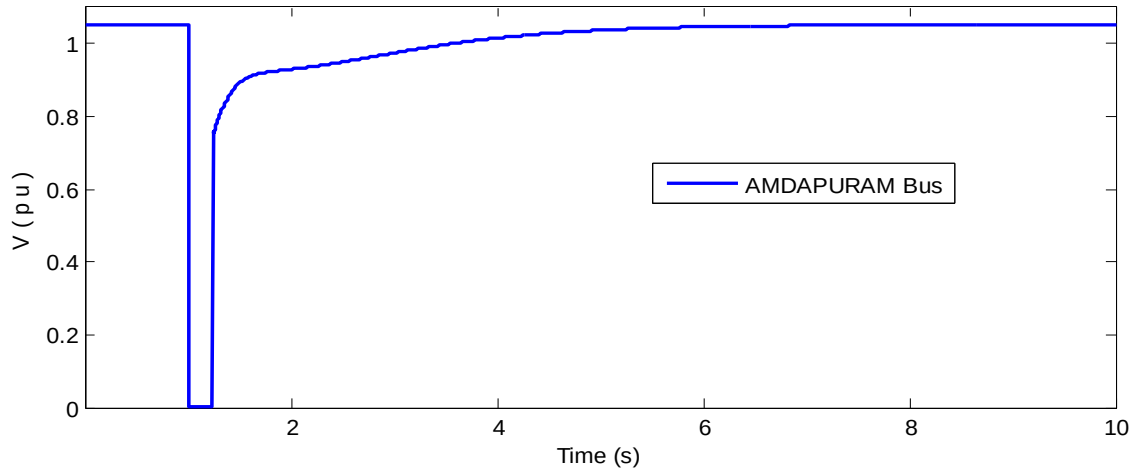


Figure 6.14.a Voltage variations at Amdapuram bus for three phase fault

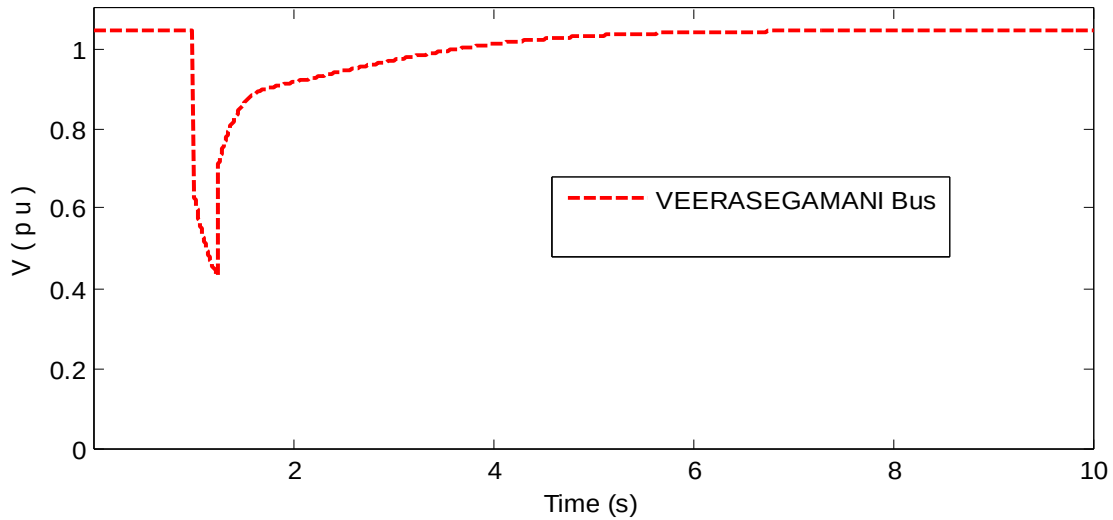


Figure 6.14.b Voltage variations at Veerasegamani bus for three phase fault

It is observed from Figure 6.14.a that the Amdapuram bus voltage regains to 1 p.u and reaches steady state after the removal of fault. It is also observed from Figure 6.14.b that fault at Amdapuram bus causes a sudden dip in voltage at nearby Veerasegamani bus during fault and regains steady-state voltage after clearing the fault. The wind farms located at these locations have fault-ride through capability.

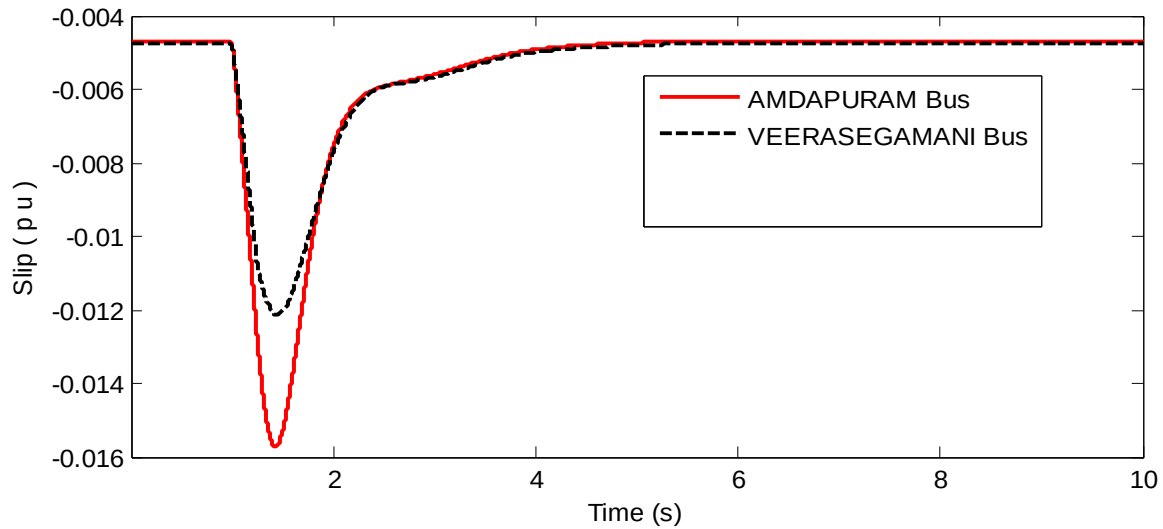


Figure 6.14.c Slip variations of Amdapuram bus and Veerasegamani bus for three phase fault.

From Figure 6.14.c it can be noted that the wind farms at Veerasegamani bus undergoes an increase in slip in the negative direction. Slip is increasing in the negative direction means that the induction generators rotors are over speeding beyond the rated speed. But after the clearance of fault the machines have regained their steady-state speed. Hence, the system is stable for this fault.

Similarly the fault is applied at various buses in Tirunelveli region and found that the system remains stable after the clearance of fault.

6.10 Summary

The dynamic models of various power system components are presented. The algorithm for analyzing the stability of the power system is described. The stability of the system and the fault-ride through capability of the wind farms are analyzed for different fault locations.

7. Conclusions and Recommendations

Based on the aforesaid analysis, the following recommendations are drawn for effective utilization of the installed wind power generation.

- When the wind penetration is below 50% the exiting transmission corridor is sufficient to evacuate the power. When it is above 50% it is observed that more number of transmission lines and transformers are overloaded. Hence, it is recommended that in order to efficiently utilize the available wind potential it is essential to establish a dedicated 765/400kV and 230 kV substations and necessary committed expansion proposals should be implemented as early as possible in the Tirunelveli region.
- The real and reactive power losses are increased as wind power penetration increases, so reactive compensation is required at the wind farm substations. Dynamic compensation at the 110 kV/230 kV substations is recommended.
- The plan for future expansion of wind turbine generators may be covered near the strong points identified in the grid.
- Weak points identified using short-circuit analysis are prone to power evacuation problem in case of increasing wind turbine generator installation.
- The transmission expansion plans in the pipe line may have a provision for installation of TCSC, as it enhances the loading of the transmission lines.
- To overcome the technical difficulties like alleviation of line over loading, reactive power compensation etc, formation of VSC based Multi terminal DC system is a viable solution.
- Stability analysis reveals that when the wind generators possess Low Voltage Ride Through (LVRT) capability there were no stability and low voltage problems. So it is necessary that the wind generators should have LVRT capability.

Appendix A

Study system data collection through field visit

Bus details				
Total No of Buses			: 156	
Number of 400kV buses			: 2	
Number of 230kV buses			: 19	
Number of 110kV buses			: 108	
Actual No	Bus no	Bus Name	kV	Bus Description
1	1	TTPSGEN	15	TTPS_GENERATOR_BUS_5X210MW
2	2	KODAGEN6	11	KODAIYAR_GENERATOR_1X60MW
3	3	KODAGEN4	11	KODAIYAR_GENERATOR_BUS_1X40MW
4	4	PERIYGEN	11	PERIYAR_GENERATOR_1X140
5	5	SURULGEN	11	SURULIYAR_GENERATOR_BUS_1X35MW
6	6	IBCPPGEN	15	IBCPPGENERATOR_BUS_1X200MW
7	7	BIOEPGEN	11	BIOMASS_NEAR_EPPOTHUMVENTRAN_1X20MW
8	8	BIOMEGEN	11	BIOMASS_GENERATOR_MELAKALLOOR
9	9	SERVAGEN	11	SERVALAR_HYDRO_GENERATOR_BUS_1X20MW
10	10	PAPANGEN	11	PAPANASAM_HYDRO_GENERATOR_BUS_1X32MW
201	11	SRPUDUR2	230	SRPUDUR_230/110/11kVSS
202	12	SANKANE2	230	SANKANERI_230/110/11kVSS
203	13	UDAYTHR2	230	UDAYTHUR_230/110 kVSS
204	14	KUDANKU2	230	KUDANKULAM_STARTUP_BUS_230/33kV
205	15	TUTICOR2	230	TUTICORIN_AUTO230/110 kV
206	16	ABPATT42	230	ABPATTY_TIRUNELVELI_PGCIL400/230 kV
207	17	KAYATHR2	230	KAYATHAR_230/110/66kVSS
208	18	VEERANM2	230	VEERANAM230/33 kVSS
209	19	TTPS2	230	TTPS_SWITCHYARD_230/15.75kV
210	20	KODIKUR2	230	KODIKURCHI230/110 kVSS

211	21	AMDAPUR2	230	AMDAPURAM230/33 kVSS
212	22	STERLIT2	230	STERLITE_230/110kV
213	23	SIPCOT2	230	SIPCOT230/110 kV
214	24	ANUPKUL2	230	ANUPPANKULAM230/110 kVSS
215	25	CHEKKA42	230	CHEKKANOORANI400/230 kVSS
216	26	PASUMAL2	230	PASUMALAI230/110kVSS
217	27	MEELAVE2	230	MEELAVETAN230/110 kVSS
218	28	PARAMAG2	230	PARAMAGUDI 230/110kVSS
219	29	IBCPP2	230	IND BHARATH 230KVSY
400	30	CHEKKAN4	400	CHEKKANURANI_400/230_KV_SS
401	31	ABPATTY4	400	ABISHEKAPATTY_THIRUNELVELI_PGCIL
1000	32	CHEMPONV	110	CHEMPONVILAI_110/11 kV
1001	33	THENGAM	110	THENGAMPUDUR_110/11 kV
1002	34	KANYAKUM	110	KANYAKUMARI_110/11 kV
1003	35	MUNCHIRA	110	MUNCHIRAI_110/11 kV
1005	36	MEENAKSH	110	MEENAKSHIPURAM_110/11 kV
1007	37	KULTHURA	110	KULTHURAI_110/11 kV
1008	38	NAGARKOI	110	NAGARKOIL_110/11 kV
1009	39	THUCKALA	110	THUCKALAY_110/11 kV
1010	40	MAHARAJA	110	MAHARAJAPURAM_110/11 kV
1011	41	SRPUDU21	110	SR PUDUR_230/110/11 kV_110/230kV
1012	42	KARUNKUL	110	KARUNKULAM_110/11 kV
1013	43	PALAVOOR	110	PALAVOOR_110/11 kV
1015	44	VEEYANOO	110	VEEYANOOR_110/11 kV
1016	45	CHIDAMBA	110	CHIDAMBARAPURAM_110/11 kV
1017	46	ARALVOIM	110	ARALVOIMOZHI_110/11 kV
1018	47	SANKAN21	110	SANKANERI_230/110/11kVSS
1019	48	IRUKKAND	110	IRUKKANDURAI_110/33/11 kV SS
1020	49	MUPANTHA	110	MUPANTHAL_110/11kVSS
1021	50	PECHIPAR	110	PECHIPARAI_110/11 kV

1022	51	PERUNGUD	110	PERUNGUDI_110/33/11kVSS
1023	52	KOODANKU	110	KOODANKULAM_110/11 kV_110/33kV
1024	53	RADHAPUR	110	RADHAPURAM_110/11 kV_110/33kV
1025	54	VADDAKKA	110	VADDAKKANKULAM_110/11 kV_110/33kV
1026	55	KODA6YAR	110	KODIAYAR_6SWITCHYARD
1027	56	PANAGUDI	110	PANAGUDI_110/11 kV_110/33kV
1028	57	ANNANAGA	110	ANNANAGAR_110/33/11kVSS
1029	58	UDAYTR21	110	UDAYTHUR_230/110/33kVSS
1030	59	KODA4YAR	110	KODAIYAR_40MW_SWITCHYARD
1032	60	THANDAIY	110	THANDAIYARKULAM_110/11 kV_110/33kV
1034	61	KALAKAD	110	KALAKAD_110/11 kV
1035	62	KOTTAIKA	110	KOTTAIKARUNKULAM 110/11kVSS
1037	63	VALLOYOO	110	VALLOYOOR_110/11 kV
1038	64	THIRUVIR	110	THIRUVIRUNTHANPULLAI_110/11 kVSS
1039	65	SATHANK	110	SATHANKULAM_110/11 kV_110/33kV
1040	66	UDANGUDI	110	UDANGUDI_110/11 kV
1041	67	ARUMUGAN	110	ARUMUGANERI_110/11kV_110/33kV
1042	68	KARANTHA	110	KARANTHANERI_110/11kV
1043	69	MANJANEE	110	MANJANEER KAYAL_110/11kV
1044	70	VEERAVAN	110	VEERAVANALLUR_110/11kV
1045	71	MELAKALO	110	MELAKALOOR_110/11kVSS
1047	72	PALAYAPE	110	PALAYAPETTAI_110/11kV
1048	73	VMCHATHR	110	VMCHATHRAM_110/11kV
1049	74	PAPANASA	110	PAPANASAM HYDEL P.H_Switch yard
1051	75	THALAIYU	110	THALAIYUTU_110/11kV_110/33
1053	76	SERVALAR	110	SERVALAR HYDEL P.H_Switch yard
1055	77	OTHULUKK	110	OTHULUKKARPATI_110/33kV_230/33kV
1057	78	RASTHA	110	RASTHA_110/33kV
1058	79	MANNUR	110	MANNUR_110/11kV
1059	80	KEELAVEE	110	KEELAVEERANAM_110/11kV_110/33kV

1060	81	KADAYAM	110	KADAYAM_110/11kV
1061	82	SUNDANKU	110	SUNDANKURCHI_110/11kV
1063	83	AYYANARO	110	AYYAANAROOOTHUR_110/11kV
1064	84	SANKTOFF	110	SANKARANKOVIL_TOFF
1065	85	ALANKULA	110	ALANKULAM_110/11kV_110/33kV
1068	86	PAVOORCH	110	PAVOORCHATRAM_110/11kV_110/33kV
1069	87	VANNIKON	110	VANNIKONENTHAL_110/11kVSS
1071	88	CHETTIKU	110	CHETTIKURICHI_110/33kV
1072	89	SURANDAI	110	SURANDAI_110/11kV
1073	90	UTHUMALA	110	UTHUMALAI_110/33kV_66/11kV
1074	91	AYYANAPU	110	AYYANAPURAM_110/11kV_110/33kV
1077	92	MALAYANK	110	MALAYANKULAM_110/11kV
1078	93	EPPOTHUM	110	EPPOTHUMVENTRAN_110/11kV_110/33kV
1080	94	VELATHIK	110	VELATHIKULAM_110/11kV
1081	95	TENKASI	110	TENKASI_110/11kV
1082	96	SHENKOTT	110	SHENKOTTAI_110/11kV
1083	97	KODIKU21	110	KODIKURCHI_110/33kV
1087	98	KOVILPAT	110	KOVILPATTI_110/11 kV
1088	99	VIJAYAPU	110	VUJAYAPURAI_110/11 kV
1089	100	SANKARAN	110	SANKARANKOIL_110/11 kV
1090	101	NSUBBIAH	110	NSUBBIAHPURAM_110/11 kV
1092	102	KADAYANA	110	KADAYANALLOR_110/11 kV
1093	103	PULIYANG	110	PULIYANGUDI_110/11 kV
1094	104	NARAYANA	110	NARAYANAPURAM_110/11 kV
1095	105	VISWANAT	110	VISWANATHAPERI_110/11 kV
1096	106	PERUMALP	110	PERUMALPATTI_110/11kV SS
1097	107	SETHIUR	110	SETHIUR_110/11 kV
1098	108	RAJAPALA	110	RAJAPALAYAM_110/11 kV
1099	109	MUDUNGAI	110	MUDUNGAIYUR_110/11 kV
1100	110	SURULIYA	110	SURULIYAR HYDEL_Switch yard

1101	111	PERIYAR	110	PERIYAR HYDEL P.H_Switch yard
1102	112	BIOEPPOT	110	BIOMASS_EPPOTHUMVANTENTRAN_BUS110kVBUS
1103	113	VEERASEG	110	VEERASEGAMANI_110/66/33kV
1104	114	KAYATR21	110	KAYATHAR_230/110/11kVSS
1105	115	VEERAN21	110	VEERANAM_230/110/11kVSS
1106	116	TUTICO21	110	TUTICORIN_110kV
1107	117	AMDAPU21	110	AMDAPURAM_110kV
1108	118	ANUPPA21	110	ANUPPANKULAM_110kV
1109	119	SHIPCO21	110	SHIPCOT_110kV
1110	120	MEELA21	110	MEELAVETAN_110kV
1111	121	STERLT21	110	STERLITE_110kV
1122	122	BIOMELAK	110	BIOMASS_MELAKALLOOR
1123	123	MEENTOFF	110	MEENAKSHIPURAM_TOFF
1124	124	NAGATOFF	110	NAGARKOVIL_TOFF
1125	125	MARTTOFF	110	MARTHANDAM_TOFF
1126	126	AMBATOFF	110	AMBASAMUTHURAM_TOFF
1127	127	THATOFF1	110	THALAYUTHU_TOFF
1128	128	THATOFF2	110	THALAYUTHU_TOFF2
1129	129	MUPPTOFF	110	MUPPANTHAL_TOFF
1130	130	PALATOFF	110	PALAVOOR_TOFF
1131	131	PERUTOFF	110	PERUNGUDI_TOFF
1132	132	TENKTOFF	110	TENKASI_TOFF
1133	133	KODITOFF	110	KODIKURICHI_TOFF
1134	134	MUNCTOFF	110	MUNCHIRAI_TOFF
1135	135	KANGAIKO	110	KANGAIKONDAN_110/11kVSS
1136	136	VISWTOFF	110	VISWANATHAPERI_TOFF
1137	137	POIGAISS	110	POIGAI_110/33kVSS
1138	138	RAJTOFF1	110	RAJAPALAYAM_TOFF1_SURULIYAR
1139	139	RAJTOFF2	110	RAJANPALAYAM_TOFF2_MUNGAIYUR

Transformer details

From Bus Name	To Bus Name	R (p.u)	X (p.u)	TAP	MVA
PAPANASA	PAPANGEN	0.01376	0.27521	1	45
SERVALAR	SERVAGEN	0.02164	0.43279	1	30
INDBARTH	BIOEPGEN	0.04187	0.83742	1	13
BIOMELAK	BIOMEGEN	0.04187	0.83742	1	13
SANKANE2	SANKAN21	0.0025	0.04994	0.99837	200
UDAYTHR2	UDAYTR21	0.0025	0.04994	0.99837	200
TUTICOR2	TTPSAUTO	0.0025	0.04994	0.99837	200
VEERANM2	VEERAN21	0.0025	0.04994	0.99837	200
KODIKUR2	KODIKU21	0.0025	0.04994	0.99837	200
SIPCOT2	TSIPCOT1	0.0025	0.04994	0.99837	200
SIPCOT2	MEELA21	0.0025	0.04994	0.99837	200
ANUPKUL2	ANUPPA21	0.0025	0.04994	0.99837	200
IBCPP2	IBCPPGEN	0.0012	0.02409	0.92616	480
CHEKKAN4	CHEKKA42	0.00079	0.01585	1	630
ABPATY4	ABPATT42	0.00079	0.01585	1	630
KAYATHR2	KAYATR21	0.00166	0.03329	0.99837	300
KODA6YAR	KODAGEN6	0.00459	0.09174	1	135
KODAYAR1	KODAGEN4	0.00717	0.14338	1	75
SURULIYA	SURULGEN	0.01872	0.18719	1	48
PERIYAR_	PERIYGEN	0.01189	0.2378	1	42
SRPUDUR2	SRPUDU21	0.001	0.01998	0.99837	500
TTPS2	TTPSGEN	0.00048	0.00963	0.92616	1200

Shunt connection (admittance) data

Bus no	Bus Name	G (p.u)	B (p.u.)	MVAR
1000	CHEMPONV	0	0.168	16.8
1003	MUNCHIRA	0	0.168	16.8
1002	KANYAKUM	0	0.168	16.8
1013	PALAVOOR	0	0.168	16.8
1049	PAPANASA	0	0.168	16.8
1038	THIRUVIR	0	0.168	16.8
1011	SRPUDU21	0	0.168	16.8
1104	KAYATR21	0	0.168	16.8
1128	THATOFF2	0	0.168	16.8
1098	RAJAPALA	0	0.168	16.8
1040	UDANGUDI	0	0.168	16.8

Generator data

S.no	Bus No	BusName	P _G MW	Qmin(MVAR)	Qmax(MVAR)	V (p.u)	MVA
1	1	TTPSGEN	1050	0	350	1.05	1235
2	2	KODAGEN6	0	0	20	1.025	87.5
3	5	SURULGEN	0	0	10	1.025	68.75
4	3	KODAGEN4	0	0	0	1.025	52.5
5	4	PERIYGEN	20	0	100	1.05	162.5
6	6	IBCPPGEN	120	-90	100	1.025	247
7	7	BIOEPGEN	8	0	11	1	26
8	8	BIOMEGEN	8	0	11	1	26
9	9	SERVAGEN	20	0	5	1.025	20
10	10	PAPANGEN	8	0	20	1.025	32

Load data

S.no	Bus No	BusName	P _L MW	Q _L MVAR
1	1000	CHEMPONV	10	4.843
2	201	SRPUDUR2	6	2.906
3	1002	KANYAKUM	14	6.781
4	1003	MUNCHIRA	27	13.08
5	1007	KULTHURA	24	11.62
6	1008	NAGARKOI	25	10
7	1009	THUCKALA	22	10.66
8	1010	MAHARAJA	1	0.484
9	1012	KARUNKUL	2.5	1.211
10	1015	VEEYANOO	20	9.686
11	1023	KOODANKU	14	6.781
12	1027	PANAGUDI	6	2.906
13	1034	KALAKAD	14	6.781
14	1039	SATHANK	34	16.47
15	1045	MELAKALO	15	7.265
16	1051	THALAIYU	16	7.749
17	1058	MANNUR	12	5.812
18	1059	KEELAVEE	9	4.359
19	1072	SURANDAI	7	3.39
20	1089	SANKARAN	16	7.749
21	1078	EPPOTHUM	39	18.89
22	1093	PULIYANG	9	4.359
23	1137	POIGAISS	6.3	3.051
24	1095	VISWANAT	10	4.843
25	1060	KADAYAM	11	5.328
26	1040	UDANGUDI	14	6.781
27	1041	ARUMUGAN	21	10.17
28	1044	VEERAVAN	15	7.265

29	1074	AYYANAPU	1	0.484
30	1081	TENKASI	9	4.359
31	1083	KODIKU21	10.8	5.231
32	1092	KADAYANA	8	3.875
33	1097	SETHIUR	12	5.812
34	1110	MEELA21	6.3	3.051
35	1099	MUDUNGAI	17	8.233
36	1104	KAYATR21	102	49.4
37	216	PASUMAL2	48	23.25
38	1106	TUTICO21	13	6.296
39	213	SIPCOT2	43	20
40	209	TTPS2	94	45.53
41	1017	ARALVOIM	2	0.969
42	1020	MUPANTHA	1	0.484
43	1021	PECHIPAR	12	5.812
44	1024	RADHAPUR	4	1.937
45	1057	RASTHA	29	14.05
46	1103	VEERASEG	11	5.328
47	1109	SHIPCO21	14	6.781
48	400	CHEKKAN4	-69	-22
49	218	PARAMAG2	-36	-12

Transmission Line Data

From BUS	To BUS	R Ω /k.m	X Ω /k.m	B/2 Ω /k.m	MVA Rating	km
SRPUDUR2	SANKANE2	0.00404	0.02248	0.02135	295	28.7
SRPUDUR2	KUDANKU2	0.0059	0.03281	0.03117	295	41.9
SANKANE2	UDAYTHR2	0.00203	0.0113	0.01073	295	14.4
SANKANE2	KAYATHR2	0.01292	0.07189	0.06828	295	91.9
SANKANE2	ABPATT42	0.01602	0.08918	0.0847	295	114
UDAYTHR2	KAYATHR2	0.01159	0.0645	0.06126	295	82.4
ABPATT42	KAYATHR2	0.00439	0.02256	0.02083	295	28.8
ABPATT42	VEERANM2	0.00475	0.02442	0.02255	295	31.2
VEERANM2	KAYATHR2	0.01359	0.06981	0.06446	295	89.2
KAYATHR2	TUTICOR2	0.0079	0.04056	0.03746	295	51.8
KAYATHR2	TTPS2	0.00396	0.02035	0.07516	590	52
KAYATHR2	ANUPKUL2	0.00974	0.05422	0.0515	295	69.3
KAYATHR2	CHEKKA42	0.01042	0.05798	0.22028	590	148
VEERANM2	KODIKUR2	0.00373	0.01917	0.0177	295	24.5
KODIKUR2	AMDAPUR2	0.00214	0.01192	0.0453	590	30.5
AMDAPUR2	CHEKKA42	0.00784	0.04365	0.16581	590	112
CHEKKA42	TTPS2	0.01042	0.05798	0.22028	590	148
CHEKKA42	SIPCOT2	0.0007	0.00391	0.00372	295	5
CHEKKA42	PASUMAL2	0.0011	0.00611	0.02321	590	15.6
PASUMAL2	TTPS2	0.01935	0.1077	0.10229	295	138
PASUMAL2	ANUPKUL2	0.01052	0.05854	0.0556	295	74.8
ANUPKUL2	STERLIT2	0.01306	0.07267	0.06902	295	92.9
STERLIT2	TTPS2	0.00229	0.01174	0.01084	295	15
TTPS2	KUDANKU2	0.01871	0.0961	0.08874	295	123
TTPS2	SIPCOT2	0.00186	0.00955	0.00882	295	12.2
SIPCOT2	PARAMAG2	0.0149	0.08296	0.07879	295	106
TTPS2	TUTICOR2	0.00035	0.00196	0.00743	590	5
THENGAM	KANYAKUM	0.01534	0.03942	0.00207	90	12
MEENAKSH	NAGARKOI	0.01541	0.03959	0.00207	90	12.1
NAGARKOI	SRPUDU21	0.01932	0.04964	0.0026	90	15.1
SRPUDU21	THUCKALA	0.03196	0.08213	0.0043	90	25
PECHIPAR	KODAYAR1	0.01759	0.0302	0.00142	90	8.7
VEEYANOO	KODAYAR1	0.02256	0.05798	0.00304	90	17.6
KANYAKUM	MAHARAJA	0.01524	0.03916	0.00205	90	11.9
KARUNKUL	MAHARAJA	0.00442	0.01137	0.0006	90	3.5
PERUNGUD	PERUTOFF	0.01662	0.04271	0.00224	90	13
SRPUDU21	ARALVOIM	0.01405	0.02412	0.00114	90	6.9
SRPUDU21	PANAGUDI	0.01931	0.04961	0.0026	90	15.1

MUPANTHA	ARALVOIM	0.00499	0.01283	0.00067	90	3.9
PERUNGUD	CHIDAMBA	0.00849	0.02181	0.00114	90	6.6
IRUKKAND	CHIDAMBA	0.00977	0.0251	0.00131	90	7.6
VADDAKKA	PERUNGUD	0.00458	0.01176	0.00062	90	3.6
VADDAKKA	THANDAIY	0.00703	0.01807	0.00095	90	5.5
SATHANK	UDANGUDI	0.02047	0.05259	0.00276	90	16
SATHANK	ARUMUGAN	0.03452	0.0887	0.00465	90	27
ARUMUGAN	MANJANEE	0.01302	0.03344	0.00175	90	10.2
SANKAN21	IRUKKAND	0.00906	0.02329	0.00122	90	7.1
RADHAPUR	PANAGUDI	0.01598	0.04106	0.00215	90	12.5
RADHAPUR	UDAYTR21	0.01918	0.04928	0.00258	90	15
RADHAPUR	KOTTAIKA	0.02685	0.06899	0.00361	90	21
THANDAIY	ANNANAGA	0.01215	0.03121	0.00163	90	9.5
VALLIYUR	ANNANAGA	0.01509	0.03876	0.00203	90	11.8
VALLIYUR	KARANTHA	0.02225	0.05716	0.00299	90	17.4
KARANTHA	THIRUVIR	0.02888	0.07421	0.00389	90	22.6
KARANTHA	KALAKAD	0.0166	0.04264	0.00223	90	13
PALAYAPE	MELAKALO	0.02195	0.05641	0.00295	90	17.2
KODAYAR1	MELAKALO	0.07134	0.14092	0.007	90	41.6
KODAYAR1	VEERAVAN	0.05114	0.1314	0.00688	90	40
BIOMELAK	MELAKALO	0.00032	0.00082	0.00004	90	0.3
VMCHATHR	ARUMUGAN	0.06152	0.10564	0.00498	90	30.3
PAPANASA	SERVALAR	0.00479	0.01232	0.00258	180	7.5
EPPOTHUM	AYYANAPU	0.02895	0.07438	0.0039	90	22.6
EPPOTHUM	VELATHIK	0.02341	0.06015	0.00315	90	18.3
EPPOTHUM	INDBARTH	0.00174	0.00447	0.00023	90	1.4
PAVOORCH	KODIKU21	0.0206	0.05292	0.00277	90	16.1
TENKASI	SHENKOTT	0.00923	0.02372	0.00124	90	7.2
TENKASI	KADAYAM	0.02398	0.06163	0.00323	90	18.8
KADAYANA	PULIYANG	0.01279	0.03285	0.00172	90	10
VEERASEG	UTHUMALA	0.00533	0.0137	0.00072	90	4.2
SURANDAI	UTHUMALA	0.01902	0.04888	0.00256	90	14.9
VANNIKON	UTHUMALA	0.01534	0.03942	0.00207	90	12
AYYANARO	SANKTOFF	0.04475	0.11498	0.00602	90	35
SURANDAI	KEELAVEE	0.02363	0.06071	0.00318	90	18.5
KEELAVEE	ALANGUW1	0.0039	0.01002	0.00052	90	3
SUNDANKU	AYYANARO	0.00256	0.00657	0.00034	90	2
MALAYANK	VEERASEG	0.02526	0.06491	0.0034	90	19.8
VISWTOFF	SANKARAN	0.0358	0.09198	0.00482	90	28
VISWANAT	NARAYANA	0.02005	0.05151	0.0027	90	15.7
PULIYANG	NARAYANA	0.01599	0.0411	0.00215	90	12.5

VISWTOFF	VISWANAT	0.00511	0.01314	0.00069	90	4
PERIYAR	SURULIYA	0.01714	0.04405	0.00231	90	13.4
PERIYAR	MUDUNGAI	0.03836	0.09855	0.00516	90	30
RAJAPALA	RAJTOFF2	0.0055	0.01413	0.00074	90	4.3
MALAYTOF	SANKARAN	0.01406	0.03614	0.00189	90	11
NSUBBIAH	VIJAYAPU	0.02055	0.05279	0.00277	90	16.1
SRPUDU21	MEENTOFF	0.01809	0.03107	0.00146	90	8.9
CHETTIKU	AYYANARO	0.01017	0.01745	0.00082	70	5
THUCKALA	MARTTOFF	0.00869	0.02234	0.00117	90	6.8
VEEYANOO	PECHIPAR	0.02257	0.05798	0.00304	90	17.6
VEEYANOO	MARTTOFF	0.00323	0.00831	0.00044	90	2.5
AMBATOFF	PAPANASA	0.00256	0.00657	0.00034	90	2
VEERAVAN	THATOFF1	0.03392	0.08715	0.00457	90	26.5
THATOFF1	THALAIYU	0.00729	0.01873	0.00098	90	5.7
PALAYAPE	THATOFF2	0.00768	0.01974	0.00103	90	6
THATOFF2	THALAIYU	0.00729	0.01873	0.00098	90	5.7
SRPUDU21	MUPPTOFF	0.01204	0.03095	0.00162	90	9.4
MUPPTOFF	MUPANTHA	0.0006	0.00154	0.00008	90	0.5
MUPANTHA	KANNAULR	0.00304	0.00782	0.00041	90	2.4
PALATOFF	PALAVOOR	0.00153	0.00394	0.00021	90	1.2
SRPUDU21	PERUTOFF	0.01202	0.03088	0.00162	90	9.4
SRPUDU21	KANNAULR	0.01667	0.04284	0.00224	90	13
TENKASI	KADNATOF	0.00895	0.023	0.0012	90	7
TENKTOFF	KADNATOF	0.00128	0.00329	0.00017	90	1
VISWANAT	KADAYANA	0.02005	0.05151	0.0027	90	15.7
TENKTOFF	KODITOFF	0.00384	0.00986	0.00052	90	3
KODITOFF	KODIKU21	0.00256	0.00657	0.00034	90	2
KODITOFF	KODIKURI	0.00038	0.00099	0.00005	90	0.3
KULTHURA	MARTHADM	0.00588	0.01511	0.00079	90	4.6
PERUTOFF	PALAVOOR	0.00614	0.01577	0.00083	90	4.8
MEENTOFF	MEENAKSH	0.00302	0.00775	0.00041	90	2.4
MEENTOFF	THENGAM	0.01818	0.03121	0.00147	90	8.9
KANNAULR	PALAVOOR	0.00801	0.01375	0.00065	70	3.9
PALATOFF	KARUNKUL	0.00767	0.01971	0.00103	90	6
MUPPTOFF	PERUNGUD	0.00499	0.01281	0.00067	90	3.9
KAYATR21	MANURTO	0.02595	0.06669	0.00349	90	20.3
KAYATR21	AYYANARO	0.02557	0.0657	0.00344	90	20
KAYATR21	THATOFF2	0.01524	0.03916	0.00205	90	11.9
ANUPPA21	NSUBBIAH	0.02941	0.07556	0.00396	90	23
ANUPPA21	KOVILPAT	0.04328	0.1112	0.00583	90	33.8
TSIPCOT1	AYYANAPU	0.01844	0.04737	0.00248	90	14.4

TTPSAUTO	MANJANEE	0.01845	0.0474	0.00248	90	14.4
TTPSAUTO	ARUMUGAN	0.02762	0.07096	0.00372	90	21.6
KODA6YAR	KODAYAR1	0.00767	0.01971	0.00103	90	6
CHEKKAN4	ABPATTY4	0.0015	0.01676	0.89633	1390	162
SETHIUR	PERUMALP	0.0179	0.04599	0.00241	90	14
SETHIUR	RAJTOFF1	0.00936	0.02405	0.00126	90	7.3
KAYATR21	VIJAYAPU	0.01854	0.04763	0.0025	90	14.5
KOTTAIKA	SATHANK	0.02685	0.06899	0.00361	90	21
MARTTOFF	MARTHADM	0.00767	0.01971	0.00103	90	6
RASTHA	OTHULUKK	0.03671	0.09432	0.00494	90	28.7
AMBATOFF	OTHULUKK	0.01023	0.02628	0.00138	90	8
MELAKALO	THIRUVIR	0.02888	0.07421	0.00389	90	22.6
VEERASEG	POIGAISS	0.01183	0.03039	0.00159	90	9.3
VEERASEG	KODIKU21	0.00951	0.02444	0.00128	90	7.4
VMCHATHR	KAYATR21	0.05114	0.1314	0.00688	90	40
KEELAVEE	KAYATR21	0.03963	0.10184	0.00534	90	31
EPPOTHUM	KAYATR21	0.03196	0.08213	0.0043	90	25
KODIKU21	POIGAISS	0.01828	0.04698	0.00246	90	14.3
RAJAPALA	RAJTOFF1	0.0055	0.01413	0.00074	90	4.3
MUDUNGA	RAJTOFF1	0.02301	0.05913	0.0031	90	18
SIPCOT2	IBCPP2	0.00105	0.00587	0.0223	590	15
ABPATT42	UDAYTHR2	0.01067	0.05478	0.05059	295	70
KAYATHR2	PASUMAL2	0.01836	0.10219	0.09706	295	131
MELAKALO	SERVALAR	0.00741	0.01463	0.00073	80	4.3
MELAKALO	TIRUPULI	0.0366	0.06284	0.00296	80	18
KARANTHA	TIRUPULI	0.02643	0.04538	0.00214	70	13
VADDAKKA	SANKAN21	0.00813	0.02089	0.00109	90	6.4
MUPANTHA	PANAGUDI	0.00749	0.01925	0.00101	90	5.9
TTPSAUTO	VAGAIKUL	0.03235	0.08311	0.00435	90	25.3
TTPSAUTO	TSIPCOTW	0.01662	0.04271	0.00224	90	13
TTPSAUTO	TSHIPCOT	0.0351	0.09018	0.00472	90	27.5
TSIPCOT1	TSHIPCOT	0.00288	0.00739	0.00155	180	4.5
TSIPCOT1	TUTOCORW	0.00771	0.01981	0.00104	90	6
KAYATR21	GANKAIKO	0.00669	0.01718	0.0009	90	5.2
MANURTO	MANNUR	0.00641	0.01646	0.00086	90	5
MANURTO	RASTHA	0.00744	0.01912	0.001	90	5.8
KAYATR21	THATOFF1	0.01524	0.03916	0.00205	90	11.9
KAYATR21	KOVILPAT	0.03836	0.09855	0.00516	90	30
KAYATR21	KAZHUHU	0.04091	0.10512	0.00551	90	32
KAYATR21	VKPURAM	0.06831	0.17552	0.0092	90	53.4
TUTOCORW	TTPSAUTO	0.01662	0.04271	0.00224	90	13

ANUPPA21	ALANKTOF	0.0236	0.06064	0.00318	90	18.5
ANUPPA21	PARAPTY1	0.00312	0.00802	0.00042	90	2.4
ANUPPA21	SATTURTF	0.01413	0.0363	0.0019	90	11.1
SATTUR1	SATTURTF	0.00281	0.00723	0.00038	90	2.2
ANUPPA21	ALANKULA	0.0236	0.06064	0.00318	90	18.5
ALANKTOF	ALANKULA	0.00038	0.00099	0.00005	90	0.3
ALANKTOF	REDIYA1	0.00859	0.02208	0.00116	90	6.7
RAJAPALA	REDIYA1	0.01279	0.03285	0.00172	90	10
SATTURTF	OTHULUKK	0.01305	0.03354	0.00176	90	10.2
PAPANASA	VKPURAM	0.00508	0.00873	0.00041	70	2.5
KOODATOF	SANKAN21	0.00844	0.01449	0.00068	70	4.2
MALAYTOF	MALAYANK	0.00244	0.00419	0.0002	70	1.2
MALAYTOF	AYYANARO	0.05693	0.09775	0.00461	70	28
ALANGUW1	PAVOORCH	0.01455	0.03738	0.00196	90	11.4
PAVOORCH	TENKTOFF	0.0179	0.04599	0.00241	90	14
PERUMALP	KARIVALA	0.01151	0.02957	0.00155	90	9
SURULIYA	RAJTOFF2	0.03068	0.07884	0.00413	90	24
PALATOFF	KANNAULR	0.00801	0.01375	0.00065	70	3.9
KADAYAM	KADAYTOF	0.01759	0.0452	0.00237	90	13.8
KADAYTOF	OTHULUKK	0.03233	0.08308	0.00435	90	25.3
KADAYTOF	PAPANASA	0.00703	0.01807	0.00095	90	5.5
UDAYTR21	SANKAN21	0.0179	0.04599	0.00241	90	14
KOODANKU	KOODATOF	0.00249	0.00641	0.00034	90	2
MUNCHIRA	KULTHURA	0.00979	0.02516	0.00132	90	7.7
VISWTOFF	RAJTOFF2	0.03836	0.09855	0.00516	90	30
EMPEEDIS	OTHULUKK	0.00895	0.023	0.0012	90	7

Appendix B

B1.WTGS parameters

Object	Parameter	Value
Operational parameters	Nominal output power- P	900 kW
	Cut-in wind speed- V_{cut-in}	3.5 m/s
	Rated wind speed - V_{rated}	15 m/s
	Cut-out wind speed- $V_{cut-out}$	25 m/s
Rotor	Rotor diameter - $2R$	52.2 m
	Number of blades- B	3
	Moment of inertia- J_w	$1.6 \times 10^6 \text{ kg.m}^2$
	Gear box ratio- GB	67.5
Generator	Rated power - P	900 kW
	Rated voltage- V	690 V
	Rated speed	1510 rpm
	Power factor - $\cos\phi$	0.89
	Moment of inertia- J_G	35.184 kg.m^2
Wind wheel	Coefficients	$c_1=0.5$ $c_2=67.56$ $c_3=0$ $c_4=0$ $c_5=1.517$ $c_6=16.286$

B.2.Induction Generator model data

Sl.No	Parameter	Value
1.	Stator Resistance R_s	0.0034 Ω
2.	Stator leakage Reactance X_{ls}	0.003 Ω
3.	Rotor Resistance R_r	0.055 Ω
4.	Rotor leakage Reactance X_{lr}	0.042 Ω
5.	Magnetizing Reactance X_m	1.6 Ω

Appendix C

Fault current level at various buses

The buses having fault current level between 5 p.u to 9 p.u are tabulated in Table C.1.

Table C.1. Fault level between 5 p.u to 9 p.u

Bus No	Bus Name	Fault Level (pu)
4	SURULIYAR_GENERATOR_BUS_1X35MW	5.6157
6	BIOMASS_GENERATOR_MELAKALLOOR	5.4196
14	PARAMAGUDI 230/110kVSS	5.7764
19	MUNCHIRAI_110/11 kV	5.8102
43	KALAKAD_110/11 kV	5.7916
65	VANNIKONENTHAL_110/11kVSS	5.9735
72	VELATHIKULAM_110/11kV	5.2786
83	VISWANATHAPERI_110/11 kV	5.7887
99	VAGAIKULAM_110/11kVSS	5.1018
105	KAZHUHU_110/11kVSS	5.0937
3	PERIYAR_GENERATOR_1X140	6.7086
5	BIOMASS_GENERATOR	6.2769
18	KANYAKUMARI_110/11 kV	6.7699
21	KULTHURAI_110/11 kV	6.8801
44	KOTTAIKARUNKULAM 110/11kVSS	6.3314
47	SATHANKULAM_110/11 kV_110/33kV	6.1131
54	VMCHATHRAM(PALAYAMKOTTAI)_110/11kV	6.3956
66	CHETTIKURICHI(DEVARKULAM)_110/33kV	6.6997
74	SHENKOTTAI_110/11kV	6.7378
78	SANKARANKOIL_110/11 kV	6.7706
85	SETHIUR_110/11 kV	6.5563
87	MUDUNGAIYUR_110/11 kV	6.5652
92	VEERANAM_230/110/11kVSS	6.6377
100	TSIPCOTW_110/11kVSS	6.5334
113	VISWANATHAPERI_TOFF	6.3022
7	SERVALAR_HYDRO_GENERATOR_BUS_1X20MW	7.435
17	THENGAMPUDUR_110/11 kV	7.0341
20	MEENAKSHIPURAM_110/11 kV	7.8165

22	NAGARKOIL_110/11 kV	7.5047
24	MAHARAJAPURAM_110/11 kV	7.39
26	KARUNKULAM_110/11 kV	7.7884
36	KOODANKULAM_110/11 kV_110/33kV	7.641
40	ANNANAGAR_110/33/11kVSS	7.5609
45	VALLIYUR_110/11 kV	7.2237
46	THIRUVIRUNTHANPULLAI_110/11 kV	7.5587
49	ARUMUGANERI_110/11kV_110/33kV	7.9222
50	KARANTHANERI_110/11kV	7.8625
51	MANJANEER KAYAL_110/11kV	7.6056
52	VEERAVANALLUR_110/11kV	7.5843
56	RASTHA_110/33kV	7.8476
57	MANNUR_110/11kV	7.074
60	SUNDANKURCHI_110/11kV	7.3081
61	AYYAANAROOOTHUR_110/11kV	7.701
67	SURANDAI_110/11kV	7.047
68	UTHUMALAI_110/33kV_66/11kV	7.9624
69	AYYANAPURAM_110/11kV_110/33kV	7.7174
70	MALAYANKULAM_110/11kV	7.6147
71	EPPOTHUMVENTRAN_110/11kV_110/33kV	7.9665
76	KOVILPATTI_110/11 kV	7.3454
79	NSUBBIAHPURAM_110/11 kV	7.8411
88	SURULIYAR HYDEL_Switch yard	7.627
89	PERIYAR HYDEL P.H_Switch yard	7.3336
90	BIOMASS_EPPOTHUMVANTENTRAN_BUS110kVBUS	7.7444
95	MEELAVETAN_110kV	7.2895
96	TIRUPULI 110/11 kV SS	7.9499
97	MARTHANDAM_110/11kVSS	7.7331
114	POIGAI_110/33kVSS	7.757
115	RAJAPALAYAM_TOFF1	7.8738
122	MALAYANKULAM_TOFF_110/11kV_SS	7.6367
123	ALANGULAMWIND FARM	7.8805
2	KODAIYAR_GENERATOR_BUS_1X40MW	8.105
8	PAPANASAM_HYDRO_GENERATOR_BUS_1X32MW	8.1891
10	KUDANKULAM_STARTUP_BUS_230/33kV	8.4769
23	THUCKALAY_110/11 kV	8.7395
27	PALAVOOR_110/11 kV	8.9303
29	CHIDAMBARAPURAM_110/11 kV	8.3779
30	ARALVOIMOZHI_110/11 kV	8.9794
32	IRUKKANDURAI_110/33/11 kV SS	8.311
37	RADHAPURAM_110/11 kV_110/33kV	8.1875

39	PANAGUDI_110/11 kV_110/33kV	8.9088
41	UDAYTHUR_230/110/33kVSS	8.7293
42	THANDAIYARKULAM_110/11 kV_110/33kV	8.385
58	KEELAVEERANAM_110/11kV_110/33kV	8.0139
59	KADAYAM_110/11kV	8.3412
64	PAVOORCHATRAM_110/11kV_110/33kV	8.1812
73	TENKASI_110/11kV	8.1105
77	VUJAYAPURAI_110/11 kV	8.5217
86	RAJAPALAYAM_110/11 kV	8.5423
91	VEERASEGAMANI_110/66/33kV	8.604
101	TSHIPCOT_110/11kV SS	8.8522
102	TUTOCORW_110/11kV SS	8.6177
104	MANURTOFF	8.0706
106	MEENAKSHIPURAM_TOFF	8.0804
109	PALAVOOR_TOFF	8.8584
110	PERUNGUDI_TOFF	8.8991
111	TENKASI_TOFF	8.7603
112	KODIKURICHI_TOFF	8.9285
116	RAJANPALAYAM_TOFF2_MUNGAIYUR	8.367
121	REDIYARKULAM_110/11kVSS	8.7308
125	KADAYANALLUR_110/11kV_SS	8.6476
126	KODIKURICHI_110/11kVSS	8.8465
127	KOODANKULAM_TOFF	8.0583
128	EMPEE SUGARS 2*25MW COGEN	8.4373
1	KODAIYAR_GENERATOR_1X60MW	9.825
9	SRPUDUR_230/110/11kVSS	9.7743
11	VEERANAM230/33 kV SS	9.9262
12	KODIKURCHI230/110 kV SS	9.7969
13	AMDAPURAM230/33 kV SS	9.5077
15	CHEKKANURANI_400/230_KV_SS	9.9009
16	ABISHEKAPATTY_THIRUNELVELI_PGCIL	9.6778
25	SR PUDUR_230/110/11 kV_110/230kV	9.7812
28	VEEYANOOR_110/11 kV	9.501
31	SANKANERI_230/110/11kVSS	9.2274
33	MUPANTHAL_110/11kVSS	9.4718
34	PECHIPARAI_110/11 kV	9.3855
35	PERUNGUDI_110/33/11kVSS	9.3588
38	VADDAKKANKULAM_110/11 kV_110/33kV	9.215
53	PALAYAPETTAI_110/11kV	9.8801
55	THALAIYUTU_110/11kV_110/33	9.8829
63	ALANKULAM_110/11kV_110/33kV	9.1868

75	KODIKURCHI_110/33kV	9.1605
93	TUTICORIN_110kV_SS	9.2467
94	SIPCOT_110kV	9.2825
98	KANNANALLUR_110/11kV_SS	9.2046
103	GANKAIKONDAN_110/11kVSS	9.7267
107	MARTHANDAM_TOFF	9.2182
108	MUPPANTHAL_TOFF	9.469
117	ALANKULAMTOFF	9.2158
118	PARAIPATTY 110 KV SS	9.7227
119	SATTUR TOFF	9.7322
120	SATTUR 110 KV SS	9.0611

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