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Effect of Penetration of Solar DGs on Transient Stability of Captive Power Generation Units

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Abstract: ***In this work, transient stability analysis of industrial generator units is carried out using rigorous simulation study. The effect of Solar Distributed Generator Units on transient stability of captive power units is studied in this work. Industrial system with 39 Buses is considered with one utility bus, and nine captive generation units. The total active power load of the system is 121.57 MW and reactive power demand is 56.6 MVAr. The work is carried out in two stages. In the first stage, Critical Clearing Times (CCTs) are obtained without introducing any DG. In the second stage, CCTs are obtained with four Solar Power DGs at four different load buses. Triple line to ground faults at 9 Generator buses and 7 load buses are considered for obtaining Critical Clearing Times (CCT). It is observed that transient stability of system is improved by placing DGs. For the faults on Generator buses, CCTs are improved by 14.6% with DGs on average. For the faults on load buses, CCTs are improved by 27% with DGs on average. The detailed results are tabulated in this paper.***

Keywords: Critical Clearing Time, Transient Stability, Distributed Generators.

I. INTRODUCTION

The transient stability analysis is an important area of research in power system assessment and deals with electro-mechanical oscillation of generators when they are subjected to perturbations. The variation of the rotor angle with respect to time is studied to verify and assess the stability. For any given perturbation, if the swinging of the rotor is gradually damped and rotor angles settle within the safe operating zone of the system, the power system is said to be transiently stable. Fault is simulated at a particular bus or on a line and Critical Clearing time (CCT) is evaluated for making the transient stability analysis of power system. CCT is the maximum allowable time for clearing the fault, for which the system remains stable. In the case of a faults occurring on transmission line, faulted line is separated from the healthy part of the system and then reclosed. If the time taken for separation and reclosing power system is below a threshold value, the power system remains stable. If the time taken for separation and reclosing is greater than the threshold time, the power system becomes unstable. Thus, the determination of CCT is an important task in the transient stability assessment for a given fault condition.

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Distributed generation is relatively smaller power generation units of Solar, Wind and Mini Hydro. Olulope et al worked on how hybrid DGs effect transient stability of power system [1]. All the countries in the world are now going for DGs because of various benefits [2]. Tiam et al studied the result of installation of large scale Solar PV on the transient stability [3]. Azmy studied the outcome of installing fuel cell on transient stability of power system [4]. Reza analyzed the effect of installation of huge number and capacity of DGs on transient stability [5]. It is found that penetration level of DGs is an important parameter in studying the effect on system stability. Systems with more number of sources can provide more reliability and better quality power [6]. Several researchers worked with single DG source [7-10]. The system inertia for solar PV or fuel cell is very low [11]. DGs output depends on weather conditions.

Arutchelvi and Joanne worked on power supplied to residential load from the hybrid system consisting of PV and wind system connected to power grid [12, 13]. Dali studied an isolated system which works at low voltage with energy storage facility, PV and wind for better energy management [14].

Within an year, the percentage of penetration of DGs in USA may increase by 25% than that of 2012 [15]. The relays and Circuit Breakers might not be able to operate in bi-directional power flow which would be the result of DG connection in radial networks. The controllers need to be redesigned in the present scenario to offer reliable services to remote villages. Price of electricity depends on the demand at that time of the day in countries like US. DGs can be used at peak hours. [16].

In this work, without DGs, CCTs were obtained considering faults at 17 locations. Keeping the load constant, 4 Solar DGs were introduced by reducing the active power generation on industrial generator units and grid. Again CCTs were obtained for the same number of faults and same locations. Results were compared for the two cases. Section 2 presents system modelling, Section 3 and 4 present results and conclusions respectively.

II. SYSTEM MODELLING

In this section, General Structure of the Power System, Generator Modeling and Load modeling are presented. The power system consists of transmission network and various motors and generators of wide ranges connected to it. Transmission network which is static contains, transmission lines, shunt/series fixed reactance and transformers. The dynamics associated with these components are relatively fast and therefore the transmission network is considered to be in steady state.

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The network is represented by the bus admittance matrix. The dynamical subsystems are the various generators connected to the network at various points. Fig 1 represents power system model.

A. General Structure of Power System

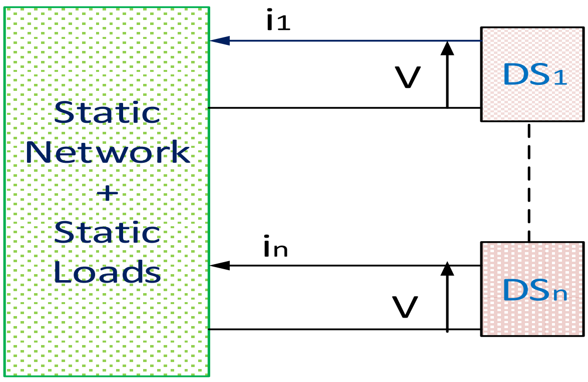

Fig.1 Representation of Power System

The modeling of generators, loads and apparatus is developed and integrated in a systematic fashion to simulate the power system transient behavior. Synchronous machine, network, Loads are three major components of modeling. The detailed modelling of generator, network, and loads is given in the following sections.

All the generators in this 39 Bus system are represented with transient circuits on both axes. The external network is modelled as equivalent generator, modelled in the same way as other generators, but with large inertia as compared to generators in Local system.

B. Generator Equations:

Stator is represented by the two axes (d and q axes) equivalent of the three-phase winding.

The flux linkages associated with d and q axes winding are given by

$$-\frac{1}{\omega_B}\dot{\psi}_d - (1+s_g)\psi_q - R_a i_d = v_d \tag{1}$$

$$-\frac{1}{\omega_B}\dot{\psi}_q + (1+s_g)\psi_d - R_a i_q = v_q \tag{2}$$

where, $s_g = \frac{w_B - w_r}{w_B}$

$$\text{and } i_d = \frac{\psi_d - E'_q}{x'_d} \tag{3}$$

$$i_q = \frac{\psi_q + E'_d}{x'_q} \tag{4}$$

For study of electromechanical dynamics it is normal to neglect stator transients as they are very fast. Consequently, pair of output algebraic equations is obtained as given by:

$$-\psi_q - R_a i_d = v_d \tag{5}$$

$$\psi_d - R_a i_q = v_q \tag{6}$$

It is assumed that the zero sequence currents in the stator are absent.

Here

ω_B is the base angular frequency in rad/s,

s_g is the generator slip,

i_d and i_q are d and q axes components of armature current,

v_d and v_q are d and q axis components of machine terminal voltage respectively.

In order to have a common axis of reference with the network v_{gd} and v_{gq} are transformed to Kron's reference frame (D-Q axes) using the transformation

$$\begin{bmatrix} v_{gd} \\ v_{gq} \end{bmatrix} = \begin{bmatrix} \text{Cos}\delta & -\text{Sin}\delta \\ \text{Sin}\delta & \text{Cos}\delta \end{bmatrix} \begin{bmatrix} v_{gD} \\ v_{gQ} \end{bmatrix} \tag{7}$$

where v_{gD} and v_{gQ} are D and Q axes components of machine terminal voltages respectively. δ is the (rotor angle) angle between the D-Q (synchronously rotating frame) axes and the d-q axes. i_D, i_Q and i_d, i_q are similarly related.Damper winding equation

$$\frac{dE'_d}{dt} = \frac{1}{T'_{q0}}[-E'_d - (x_q - x'_q)i_q] \tag{8}$$

Field winding equation

$$\frac{dE'_q}{dt} = \frac{1}{T'_{d0}}[-E'_q + E_{fd} + (x_d - x'_d)i_d] \tag{9}$$

Where, T'_{d0} and T'_{q0} are the open circuit d and q axes transient time constants and E_{fd} is the field voltage.

The relation between E'_d, E'_q and v_d, v_q are given by

$$E'_q + i_d x'_d = v_q \tag{10}$$

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$$E'_d - i_q x'_q = v_d \tag{11}$$

Swing equation:

The electrical torque of the generator is given by,

$$T_e = \frac{x'_d - x'_q}{x'_d x'_q}\psi_d \psi_q + \frac{E'_d \psi_d}{x'_q} + \frac{E'_q \psi_q}{x'_d} \tag{12}$$

From equation 2.5 and 2.6, it can be written as

$$\psi_d = E'_q + i_d x'_d \tag{13}$$

$$\psi_q = -E'_d + i_q x'_q \tag{14}$$

Substituting equation 13 and 14 into equation 12, after some manipulations, the following equation is obtain

$$T_e = i_q E'_q + i_d E'_d + i_q i_d (x'_d - x'_q) \tag{15}$$

The swing equation is given by,

$$\dot{s} = \frac{1}{2H_g}(T_m - T_e - Ds_g) \tag{16}$$

$$\frac{d\delta}{dt} = \omega_b(slip) = \omega_b(s_g) \tag{17}$$

Here, V_g is machine terminal voltage, V_s is output from PSS (not used in this study). State equation for the excitation system is,

$$\dot{E}_{fD} = -\frac{1}{T_E}E_{fd} + \frac{K_E}{T_E}(V_{ref} + V_s - V_g) \tag{18}$$

$$V_g = \sqrt{V_{gD}^2 + V_{gQ}^2} \tag{19}$$

C. Interfacing Generator to Network

The relation between E'_q, E'_d and v_d, v_q is given by,

$$E'_q + i_d x'_d = v_q \tag{20}$$

$$E'_d - i_q x'_q = v_d \tag{21}$$

This can be written as,

$$E'_q + i_d x'_d = v_q \tag{22}$$

$$E'_d - (x'_q - x'_d)i_q - i_q x'_d = v_d \tag{23}$$

This combined equation can be written as,

$$(E'_q + jE'_d) - j(i_q + ji_d)x'_d + j(x'_q - x'_d)i_q = (v_q + jv_d) \tag{24}$$

Let term $(x'_q - x'_d)i_q$ be represented by E' the above equation becomes,

$$E'_q + j(E'_d + E') - j(i_q + ji_d)x'_d = (v_q + jv_d) \tag{25}$$

On network side, this equation can be represented as,

$$(E'_q + j(E'_d + E'))*e^{j\delta} - j(i_Q + ji_D)x'_d = (v_Q + jv_D) \tag{26}$$

Where, $(i_Q + ji_D) = (i_q + ji_d)*e^{j\delta}$ and

$$(v_Q + jv_D) = (v_q + jv_d)*e^{j\delta}$$

As this equation has a term dependent on δ, it is modified as follows.

Let $E'_{dummy} = E' * e^{j\delta} = (x'_q - x'_d)i_q * e^{j\delta}$ in steady state.

Now state equation for E'_{dummy} is as follows

$$\frac{d}{dt}E'_{dummy} = \frac{1}{T_{dummy}}[-E'_{dummy} - j(x'_q - x'_d)i_q] \tag{27}$$

where T_{dummy} is open circuit time constant of dummy coil. Generally this is very low (~0.01).

The generators are modelled as constant current source with direct axis transient reactance in parallel. The Fig. 2 shows generator representation on network side. Thus the final equation can be written as,

$$E'_Q + j(E'_D + E_{dummy}) + j(i_Q + ji_D)x'_d = (v_Q + jv_D) \tag{28}$$

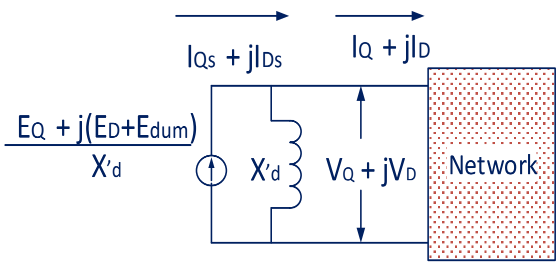

Fig. 2 Generator Representation on Network Side

where, $E'_Q + jE'_D = (E'_q + jE'_d)*e^{j\delta}$

This is an approximate treatment to include transient saliency but the degree of approximation can be directly controlled by changing T_{dummy}.The advantage in using above model is that x'_d can be included into network.

Generator internal source currents are the sum of current following into the network and current flowing into shunt.

$$i_{Ds} = i_D + \frac{v_Q}{x'_d} \tag{29}$$

$$i_{Qs} = i_Q - \frac{v_D}{x'_d} \tag{30}$$

$$i_q + ji_d = (i_{Qs} + ji_{Ds})*e^{-j\delta} \tag{31}$$

D. System Description

Industrial system with 39 Buses is considered with one utility bus and nine captive generation units including one slack bus. It is assumed that, industry imports some amount of power and remaining load is met by captive power generation units. Captive power Generation units are normally smaller in size compared to utility generator units. Industry is assumed to have nine generator units of various sizes. The system consists of 39 Buses, 34 lines and 12 transformers. Bus No.6 is considered as slack bus. The inertia of Bus No.2 is considered very large as this current study does not consider the instability of utility grid. The power from utility enters into the industry through tie lines connected between 2-11 and 2-19. The total active power load of the system is 121.57 MW and reactive power of the system is 56.6 MVAr. DGs of total capacity 27 MW are connected at four different buses. The DG penetration considered in this work is, 22 %. Fig. 3 shows the 39 Bus system.

Line data, generator and load data are presented in Table A1, A2 and A3 respectively. Two case studies have been conducted. At the first level, without including any DG, transient stability study is conducted. At the second level, Solar DGs are placed at four load buses and CCTs are obtained for various faults. The effect of solar DGs is studied.

III. RESULTS

In this work, transient stability analysis of industrial generator units is carried out using rigorous simulation study using MATLAB/Simulink. CCTs are obtained by Modified Euler Method. The Voltage magnitudes, angles and power flows before and after connecting DGs are presented in both the cases.

A. Analysis of CCTs with Solar DG

Four Solar Power DGs are considered at Bus No. 13, 15, 27 and 36. The DG capacities are 7.5 MW, 4.5 MW, 6.0 MW and 9.0 MW. This amounts to 22% of total active power demand of the loads. Faults at 9 Generator buses and 7 load buses are considered for obtaining Critical Clearing times. It is observed that the presence of DGs affects the power flows on lines. The deviation in power flows has direct impact on CCTs for various faults. Table I shows the critical clearing times before and after keeping Solar Power DGs. It is observed that for the faults at generator buses, CCTs are increased by 14.6% on average.Table II shows the voltage magnitudes and voltage angles before and after placing the DGs. It is observed that voltage magnitude increased at all the buses in the system. Voltage angles are largely varied at all the buses in the system. Because of injecting active power at four nodes, majority of the voltage angles have changed from negative to positive or large negative to small negative. Voltage at Bus 13 changed from 0.9741 to 0.9869 pu. Voltage at Bus 15 changed from 0.957 to 0.9632 pu.

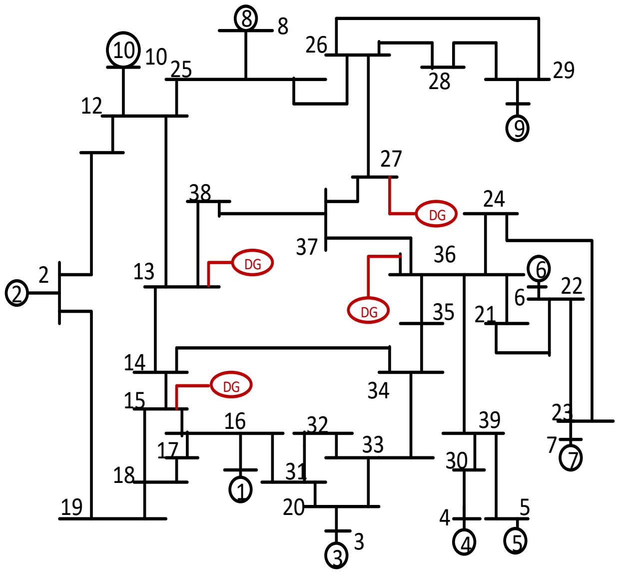

Fig. 3 Single line diagram of the 39 Bus Test System

Table I. CCT for Faults on Generator Buses with and without Solar DGs.

Bus no.	Before DG placement CCT (in Sec)	After DG placement (Solar) CCT (in Sec)	% Change	Generator that becomes unstable
1	0.37	0.43	16	Gen. 1
2	0.50	0.56	12	Gen. 10
3	0.31	0.37	19	Gen. 3
4	0.27	0.33	22	Gen. 4
5	0.33	0.37	12	Gen. 5
7	0.27	0.32	18	Gen. 7
8	0.27	0.31	14	Gen. 8
9	0.37	0.39	5	Gen. 9
10	0.37	0.42	13	Gen. 10

Voltage at Bus 27 changed from 0.9586 to 0.9697 pu. Voltage at Bus 36 changed from 0.9651 to 0.9736 pu. Table III presents the CCTs for faults at load buses. CCTs are increased by 27% on average. Total active power capacity of DGs is 18 MW and hence, same amount is reduced on captive power units and utility generator uniformly. Table IV shows the real and reactive power flows in the lines.

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Table II : Voltages magnitudes and Voltage angles before and after placing Solar DGs

	Before DG placement		After DG placement			Before DG placement		After DG placement	
Bus No.	**Voltage**	**Angle(Deg)**	**Voltage**	**Angle (Deg)**	**Bus No.**	**Voltage**	**Angle (Deg)**	**Voltage**	**Angle (Deg)**
1	1.016	-0.9251	1.016	9.3201	21	0.966	-11.9323	0.974	-0.4778
2	1.035	0.6944	1.035	10.2363	22	1.0068	-8.3431	1.0125	-1.2238
3	0.98	-3.3686	0.98	6.2729	23	1.0055	-8.8107	1.0109	-1.1815
4	1.038	-9.0227	1.038	0.8512	24	0.9635	-12.1902	0.9718	-0.572
5	1.01	-8.1657	1.01	2.6802	25	0.9877	-4.1411	0.9945	6.3422
6	1.1	0	1.1	0	26	0.9896	-10.2094	0.9912	1.8551
7	1.056	-3.575	1.056	2.5689	27	0.9586	-13.1495	0.9697	1.585
8	1.067	3.1947	1.067	12.3796	28	0.9897	-10.2621	0.9909	1.802
9	0.996	-10.0674	0.996	1.9811	29	0.9911	-10.3067	0.992	1.7694
10	1.079	4.661	1.079	13.4161	30	0.9873	-13.5375	0.9915	-2.6493
11	1.0331	0.6022	1.0337	10.1722	31	0.9322	-8.3862	0.9371	2.6219
12	1.0267	0.2133	1.0293	9.9123	32	0.8767	-11.7454	0.8823	-0.6494
13	0.9741	-6.5846	0.9869	6.2508	33	0.9328	-9.3528	0.9384	1.7572
14	0.9393	-9.8424	0.9472	1.958	34	0.9468	-10.4025	0.9541	1.1587
15	0.957	-6.3764	0.9632	5.1513	35	0.9614	-11.9312	0.9697	-0.2229
16	0.9577	-6.1179	0.9628	5.0293	36	0.9651	-12.0105	0.9736	-0.29
17	0 .9694	-4.9055	0.9736	5.6358	37	0.9661	-11.9019	0.9769	0.0329
18	0.9892	-3.1348	0.9926	7.1046	38	0.9668	-10.3509	0.978	1.9427
19	1.0315	0.6356	1.032	10.193	39	0.969	-12.0592	0.976	-0.3793
20	0.9338	-8.635	0.9386	2.2831					

Table III. CCT for Faults on load buses with and without Solar DGs

Bus no.	Before DG placement CCT (in Sec)	After DG placement (solar) CCT (in Sec)	% Change	Generator that becomes unstable
11	0.36	0.39	8	Gen. 10
12	0.30	0.32	7	Gen. 10
16	0.41	0.47	15	Gen. 1
19	0.42	0.50	19	Gen. 1
21	0.29	0.44	52	Gen. 4
35	0.34	0.51	50	Gen. 4
36	0.29	0.40	38	Gen. 4

Table IV. Real and Reactive power flows in the lines

From bus	To bus	Real power	Reactive power
27	37	1.62871	-0.72215
38	37	3.87166	-0.19876
36	24	5.31869	1.258
36	21	5.83057	-2.04684
39	36	1.08862	3.23169
37	36	5.48511	-0.6676
36	35	1.10047	3.41207
34	35	2.12593	-2.2833
33	34	0.79009	-1.60122
29	28	2.33557	1.86048
26	29	0.21073	-2.45703
26	28	1.81993	-0.99204
26	27	0.4418	1.28484
25	26	6.25979	-0.35259
24	23	0.22957	-1.26812
23	22	0.0682	-0.26245
21	22	1.08654	-4.62493
20	33	1.86882	-0.15247
31	20	1.16953	-0.46102
2	19	19.78538	11.07003
19	18	17.73609	10.67241
18	17	5.70494	3.63567
16	31	4.85302	2.64164
17	16	1.14826	1.0161
18	15	4.28757	3.13989
15	16	0.76446	0.04473
14	34	1.3411	-0.90253
15	14	5.89979	1.30745
13	38	5.48584	0.30806
13	14	3.39241	1.64738
12	25	6.61404	-1.05709
12	13	7.68971	3.788
11	12	13.15881	1.08501
2	11	14.17553	0.04402
39	30	2.71756	-1.17964
5	39	3.82	2.33101
33	32	1.07713	1.49581
31	32	1.28018	1.31497
4	30	3.58	2.67001
9	29	6.99994	5.48429
8	25	4.9	3.46338
7	23	2.6	1.78667
6	22	1.66333	6.75085
3	20	3.2	2.14068
1	16	4.95309	3.68387
10	12	3.80001	3.01335

IV. CONCLUSION

In this work, effect of Solar Power DGs on transient stability of the industrial power system is analysed. Industrial Generators are of relatively smaller capacity. Static modelling of DGs is used in this work. In this work attempt has been made to study the impact of DGs on critical clearing time of the faults at Generator Buses and faults at load buses. Four Solar DGs of different capacities were installed at four load buses simultaneously. It is observed that CCT for all the faults increases due to active power injection. The percentage change is low for faults at Generator buses and high at load buses. It is observed that for the faults at generator buses, CCTs are increased by 14.6% on average. CCTs for faults at load buses are increased by 27% on average. The amount of change in CCT for a particular fault is directly proportional to the deviation in power flow on lines between faulted bus and affected generator. Future work may be carried out with higher penetration of DGs and increased load demand.

APPENDIX

A1: Line data

Line No.	From	To	R (pu)	X (pu)
1	37	27	0.0013	0.0153
2	37	38	0.0007	0.0082
3	36	24	0.0001	0.0009
4	36	21	0.0001	0.0005
5	36	39	0.0006	0.0005
6	36	37	0.0007	0.0009
7	35	36	0.0006	0.0009
8	34	35	0.0018	0.0087
9	33	34	0.0009	0.0101
10	28	29	0.0004	0.0001
11	26	29	0.0007	0.0005
12	26	28	0.0003	0.0004
13	26	27	0.0014	0.0147
14	25	26	0.0012	0.0123
15	23	24	0.0022	0.035
16	22	23	0.0006	0.0096

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17	21	22	0.0008	0.0085
18	20	33	0.0004	0.0043
19	20	31	0.0004	0.0043
20	19	2	0.0001	0.0001
21	18	19	0.0003	0.0033
22	17	18	0.0004	0.0046
23	16	31	0.0007	0.0082
24	16	17	0.0006	0.0092
25	15	18	0.0008	0.0082
26	15	16	0.0002	0.0026
27	14	34	0.0008	0.0089
28	14	15	0.0008	0.0088
29	13	38	0.0011	0.0133
30	13	14	0.0013	0.0213
31	12	25	0.007	0.0086
32	12	13	0.0013	0.0091
33	11	12	0.0003	0.0004
34	11	2	0.0001	0.0001
35	39	30	0.0007	0.0138
36	39	5	0.0007	0.0142
37	32	33	0.0016	0.0345
38	32	31	0.0016	0.0385
39	30	4	0.0006	0.018
40	29	9	0.0001	0.0006
41	25	8	0.0006	0.0232
42	23	7	0.0005	0.0272
43	22	6	0	0.0143
44	20	3	0	0.02
45	16	1	0.0003	0.015
46	12	10	0.0003	0.0181

A2: Load data

Bus No.	P_d (pu)	Q_d(pu)
1	0.092	0.046
2	11.04	2.5
3	2.5	1.6
4	1.5	1.2
5	2	1.6
7	3	2
8	1	0.6
9	2.3	1.23
10	2.7	1.19
11	1	0.6
12	2.6	1.68
13	3	1.43
13	3.22	0.024
14	2.9	1.68
14	5	1.84
15	2.1	1.69
16	2	1.67
17	2.2	1.64
17	2.338	0.84
18	2.4	1.68
18	5.22	1.76
19	2	1.63
20	2.5	1.58
21	2	1.65
21	2.74	1.15
22	2.8	1.54
23	2.754	0.8466
24	2	1.64
24	3.086	0.922
25	2.7	1.34
25	2.24	0.472
26	1.39	0.17
26	2.35	1.66
27	2	1.45
27	2.81	0.755
28	2.06	0.276
28	2.09	1.6
29	2.835	0.269
29	2.03	1.86
30	6.28	1.03
31	2.38	1.64
32	0.075	0.88
32	2.27	1.65
35	3.2	1.53
36	3.294	0.323
38	1.58	0.3

A3 : Generator data

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Bus No.	Xd	Xd'	Td0'	Xq	Xq'	Tq0'	H	D	Ka	Ta
1	0.295	0.0347	3	0.295	0.0347	1.5	0.0583	0	25	0.025
2	0.003	0.0005	4	0.003	0.0005	0.4	5.5	0	25	0.025
3	0.2495	0.0401	4.7	0.2495	0.0401	1.5	0.0548	0	25	0.025
4	0.33	0.066	5.4	0.33	0.066	0.44	0.038	0	25	0.025
5	0.262	0.0436	5.69	0.262	0.0436	1.5	0.0476	0	25	0.025
6	0.254	0.02	7.3	0.254	0.02	0.4	0.0708	0	25	0.025
7	0.265	0.049	5.66	0.265	0.049	1.5	0.0394	0	25	0.025
8	0.26	0.057	6.7	0.26	0.057	0.41	0.0383	0	25	0.025
9	0.061	0.0097	4.79	0.061	0.0097	1.36	0.0545	0	25	0.025
10	0.2	0.034	3.4	0.2	0.034	1.04	0.068	0	25	0.025

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