Determination of Generator Steady State Stability Limit Using Losses Concept and RBFNN

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***Abstract*— In the multimachine circumstances, it is difficult to analyze the steady state stability of each generator. In previous research, analysis of the steady state stability limit has been carried out but it only looked at the stability of the overall system. Therefore, to analyze the stability of each generator, the multimachine system must be changed into a Single Machine to Infinite Bus (SMIB) system by collecting all the loads into one central load in the infinite bus. The method to change from the multimachine system to SMIB system was presented in this paper. The multimachine system was converted into an equivalent impedance (r_{eq} and x_{eq}) and an equivalent load based on losses concept. After r_{eq} and x_{eq} is calculated, the value of the maximum generation of each generator units was determined using the steady state stability limit concept. By means of maximum generation, the maximum output power limit can be generated without causing instability. Generator Saguling, which is one of the generators in the Java-Bali system 500 kV was used as a observed generator. Radial Basis Function Neural Network (RBFNN) was applied to determine the maximum generation of generator Saguling on the variety load. Therefore, the determination of the maximum generation limit of generator Saguling can be determined directly at any time change of the load demand. ETAP simulation was used to validate the calculation results of the proposed method.**

***Index Terms*— The Losses Concept; Equivalent Resistance; Equivalent Reactance; Generator Steady State Stability Limit; RBFNN.**

I. INTRODUCTION

Electric power systems that have a lot of machines usually distribute power to the load through the interconnected system. The main purpose of the interconnected system is to maintain the continuity and the availability for the increasing needs of electric power. The growing of the power system can result in poor performance when the system is disturbed[1].

It is necessary to find preventive measures to avoid severe contingencies in the power system operation and the power system stability margin of which we could say "how stable the power system is" in a given steady state [2].

Steady-state stability limit of the power system is the steady state operating condition in which the power system is still in a stable condition, but a small change of the parameters of the operation will lead to instability of the system [1-4].

Load flow method can be used to determine the steady-state stability limit of a power system by increasing the load until the load flow process becomes not convergent [5]. Continuation Power Flow Method (CPF) has also been frequently used to determine the relationship between the loading parameters to voltage at each bus [6].

Practical studies to determine the stability analysis have also been developed to decrease the mathematical equations of the Jacobian Dynamic [7] and dynamic simulation [8].

In previous research, analysis of the steady-state stability limit has been carried out [5-8], but still these researches look at the stability of the overall system only, making it difficult to analyze the stability of each bus or generator.

Therefore, to analyze the stability of each generator, the multimachine system must be changed into a SMIB system by collecting all the loads into one central load in the infinite bus.

In this paper, determinination of the maximum generation which is a generator steady state stability limit of units generator using the losses concept is provided. Maximum generation of generator is influenced by several factors: source voltage, phase angle and networks impedance value. Equivalent network impedance can be determined by knowing the losses in the network, then the multimachine system can be changed into SMIB system with an equivalent impedance and an equivalent load. Note that the determination of equivalent impedance value using losses concept has been used in [9-14] to determine the Voltage Stability Index (VSI) for SMIB system. And the example to demonstrate the features of steady state stability in a single machine connected to a infinite busbar has been used in [15]. However, the change from the multimachine system to SMIB system is not provided.

The method to change from the multimachine system to SMIB system is presented in this paper. Determinination of the maximum generation, which is a generator steady state stability limit of units generator can be calculated after the network impedance is obtained and multimachine system is changed into the SMIB system.

Generator Saguling, which is one of the generators in the Java-Bali system 500 kV was used as a observed generator. RBFNN was applied to determine the maximum generation of generator Saguling on the variety load. Therefore, the determination of the maximum generation limit of generator Saguling can be determined directly at any time change of the load demand.

II. BASIC THEORY

A. Concept of Single Machine Steady State Stabilty

Electric power system is defined as a collection of some of the power stations and substations, which are interconnected by transmitting nets with each other.

Interconnection system in operating system aims to obtain a combination of electric power generation as economical as possible, hence achieving a balance between the power available and the power is needed. System interconnection between the generators of the power system is shown in Figure1.

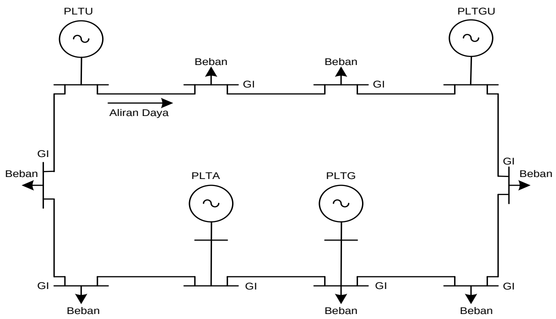

Figure 1: System interconnection of electric power systems

To analyze the steady state stability of each generator, firstly, the multimachine system must be changed to SMIB system. The method to change the multimachine system to SMIB system will discuss in Section 3.

If the system is considered to have no power loss, the power generated equals to the power delivered to the infinite bus. The equation for P_G written as:

$$P_G = \frac{|E||V|}{X_e} \sin \delta \quad (1)$$

Figure 2 shows a generator connected to an infinite bus. Bus voltage $|V|$ is the constant magnitude when the net is very large (infinite). Assuming the generator is operating at fixed excitation, maintaining fixed $|E|$ and fixed X_e, then P_G is a function of the power angle δ. The characteristics power angle is shown in Figure 3. The maximum power is delivered to an infinite bus occurred at $\delta = 90^0$. Equation (1) can be written as:

$$P_G = P = P_{max} \quad (2)$$

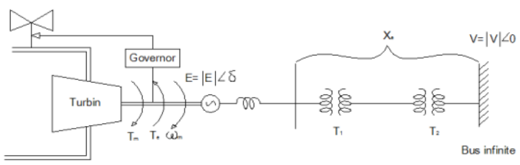

Figure 2: A generator connected to an infinite bus

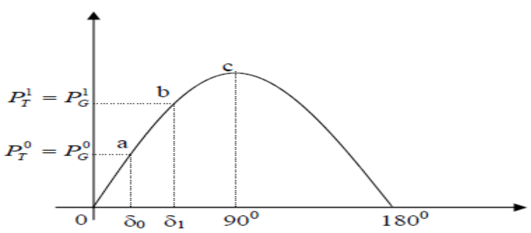

Figure 3: Characteristics of the real power and the power angle

P_{max} is the steady-state stability limit of the system, which is the maximum power that can be delivered under slow disturbance. If an attempt is made to transmit power over this power limit, the synchronism is lost. The maximum power is also referred to as the pull-out power [4].

$$P_{max} = \frac{|E||V|}{X} \quad (3)$$

where X is the reactance transfer between E and V,

$$X = X_d' + x_{eq} \quad (4)$$

$$E = V + j\,I\,X \quad (5)$$

where X_d' is generator reactance, x_{eq} is equivalent reactace, E is generator terminal voltage, I is inducted current and V is generator bus voltage, respectively.

It can be concluded that the maximum power that can be transferred by the generator is very dependent on the reactance network. If the generator transfers beyond this maximum power limit, it can lead to the instability as loss of synchronization on the generator. If the load still increases, the stator and rotor magnetic coupling will be lost.

B. Radial Basis Function Neural Network

Radial Basis Function Neural Network (RBFNN) was applied to determine the limit of the maximum generation of generator at any time change of the load demand.

Radial Basis Function Neural Network (RBFNN) is one of the artificial neural network models. RBF is a function commonly used in the regression. RBF function is applied in multi layer neural network perceptron called RBFNN.

These networks have the advantage of being much simpler than the perceptrons while keeping the major property of universal approximation of functions. Numerous techniques have been developed for RBFNN learning.

In addition, RBFNN can handle the nonlinear data that is likely equal to the conditions in the real time. RBFNN has one nonlinear hidden layer and the linear output only, so it can accelerate the computing [16]. Figure 4 shows the architecture of the RBFNN.

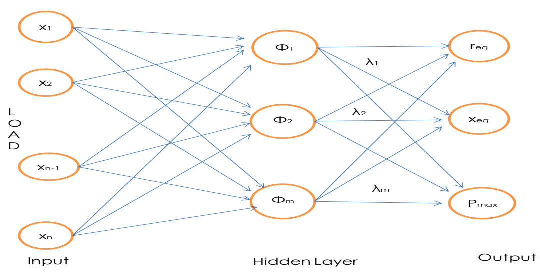

Figure 4: The architecture of the RBFNN

RBFNN models consist of three layers: the input layer, the hidden layer, and the output layer. Input layer receives an input vector x, which is then taken to a hidden layer which will process the input data as a nonlinear activation function. The output of the hidden layer is further processed in the output layer as a linear. RBFNN model uses the base functions as activation function for each neuron in the hidden layer.

III. METHODOLOGY

A. Reduction of The Multimachine System to SMIB System Using Losses Concept and Determination of Generator Steady State Stability Limit

Electric power system is a large system with multi generators (multimachine). If the generator stability analysis should be carry out in multimachine system, it will be very difficult. Therefore, the multimachine system as shown in Figure 5 must first be changed to a Single Machine to Infinite Bus (SMIB) system. The multimachine system is converted into an equivalent impedance and an equivalent load as shown in Figure 6.

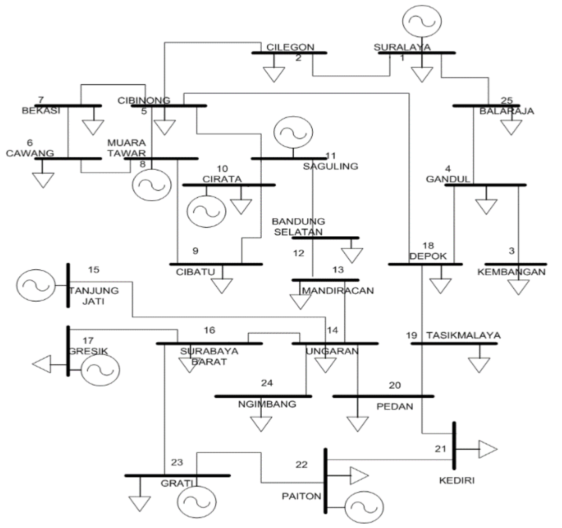

Figure 5: Java-Bali multimachine system 500 kV

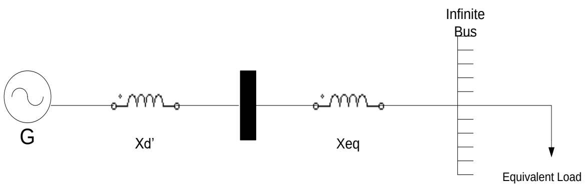

Figure 6: Single Machine to Infinite Bus (SMIB) system

The procedure to change the multimachine system to SMIB system and to calculate the maximum generation (P_{max}) of each generator unit can be explained as follows:

1. Prepare loading value data by regulating the loading such that it does not exceed the generating capacity of the observed generator (the one that stability will be analyzed and which the equivalent impedance will be calculated).
2. Running the load flow with all generators are switched off except the observed generator. Obtain the active power (P), the reactive power (Q), the active power losses (P_L) and the reactive power losses (Q_L).
3. Calculate the current value I of the observed generator using the following equation:

$$I* = \left(\frac{S_{in}}{\sqrt{3}xV_i} \right) \tag{6}$$

where:
I^* = I conjugate
S_{in} = P + jQ = generated complex power of generator
Vi = voltage of bus i

4. Equivalent current is equal to the observed generator current.
5. Calculate the equivalent value of r_{eq} and x_{eq} using the losses concept as shown in the following equations:

$$Z_{eq} = \frac{S_L}{I^2} = \frac{P_L + jQ_L}{I^2} \tag{7}$$

$$r_{eq} = Z_{eq} \cos\theta \tag{8}$$

$$x_{eq} = Z_{eq} \sin\theta \tag{9}$$

where:
S_L = P_L + jQ_L ; with S_L, P_L and Q_L are complex power losses, active power losses and reactive power losses between two bus, respectively.
Z_{eq}, r_{eq} and x_{eq} are equivalent impedance, equivalent resistance and equivalent reactance, respectively.

6. Calculate E using (5).
7. Determine the maximum generation of observed generator which is the generator steady state stability limit using (3).
8. Repeat above procedure for observed generator for variety loading value until several loading data that will be used as training value on RBFNN are received.

B. Training and Testing of RBFNN

Several data that went through the above procedure *were* used as training value on RBFNN. Input data are variety loading and output data are r_{eq}, x_{eq} and $P_{max.}$ After the training, testing was then performed on RBFNN to test the accuracy of the results obtained.

IV. SIMULATION AND RESULT

A. Reduction of The Multimachine System to SMIB System Using Losses Concept

The simulation using the 500 kV transmission system of Java-Bali that consists of 1 swing bus, 7generator bus and 17 load bus. Figure 5 shows a picture of SLD (Single Line Diagram) of Java-Bali system 500 kV.

There are 8 generators in the Java-Bali system 500 kV. The generator was connected to the load bus through the lines with the different conductor type. The generator on bus 11 e.g. generator Saguling was used as observed generator.

The simulation steps to change the multimachine system to SMIB system can be explained as follows:

1. Prepare loading value data by regulating the loading so that it does not exceed the generating capacity of the observed generator.
2. Run the load flow with all generators switched off except the observed generator. The results of the load flow with all generators switched off, except the observed generator on bus 11 are presented in Table 1.
3. From Table 1, we can see that the generated power of generator Saguling was 536.027 MW and 211.426 MVar. Voltage of bus 11 was 1,00 pu. The active power losses was 1,027 MW and the reactive power losses was -220,448 MVar.
4. The calculated result for the current value I of the observed generator using (6) was 665,358 A.
5. The r_{eq} value and the x_{eq} value can calculate using (7), (8) and (9) and we received 0,0000092792- j 0,00199184.

B. Determination of Generator Steady State Stability Limit

1. Calculate E using (5).
2. We can determine the maximum generation of observed generator which is the generator steady-state stability limit using (3), and obtained 668,929 MW.
3. Repeat the above procedure for observed generator for variety loading value until we get several loading data that will be used as training value to RBFNN.

Table 1
The load flow results for observed generator

Power Flow Solution by Newton-Raphson Method Maximum Power Mismatch = 1.15256e-006 No. of Iterations = 3							
Bus No.	Voltage Mag.	Angle Deg	Load		Generation		Injected
			MW	Mvar	MW	Mvar	Mvar
1	0.994	-0.726	7.258	4.440	0.000	0.000	0.000
2	0.994	-0.730	33.349	22.398	0.000	0.000	0.000
3	0.994	-0.697	36.052	25.753	0.000	0.000	0.000
4	0.994	-0.664	25.806	17.859	0.000	0.000	0.000
5	0.995	-0.546	33.064	21.214	0.000	0.000	0.000
6	0.995	-0.572	36.052	17.859	0.000	0.000	0.000
7	0.995	-0.586	30.645	16.774	0.000	0.000	0.000
8	0.996	-0.425	0.000	0.000	0.000	0.000	0.000
9	0.997	-0.298	39.041	31.278	0.000	0.000	0.000
10	0.999	-0.120	32.257	24.174	0.000	0.000	0.000
11	1.000	0.000	0.000	0.000	536.027	211.426	0.000
12	0.999	-0.204	27.988	34.633	0.000	0.000	0.000
13	0.996	-0.732	18.833	13.419	0.000	0.000	0.000
14	0.991	-1.612	15.607	35.817	0.000	0.000	0.000
15	0.992	-1.734	0.000	0.000	0.000	0.000	0.000
16	0.988	-2.001	40.891	31.278	0.000	0.000	0.000
17	0.988	-2.009	9.962	8.979	0.000	0.000	0.000
18	0.995	-0.688	0.000	0.000	0.000	0.000	0.000
19	0.996	-1.248	13.140	1.677	0.000	0.000	0.000
20	0.992	-1.703	24.857	24.075	0.000	0.000	0.000
21	0.990	-1.963	16.983	20.326	0.000	0.000	0.000
22	0.988	-2.109	39.800	26.838	0.000	0.000	0.000
23	0.987	-2.059	6.167	19.043	0.000	0.000	0.000
24	0.994	-0.716	34.724	28.318	0.000	0.000	0.000
25	0.989	-1.957	12.523	5.723	0.000	0.000	0.000
Total			535.000	431.874	536.027	211.426	0.000

C. Training and Testing of RBFNN

In this paper, 19 training data and 5 testing data of the generator Saguling as observed generator were used on RBFNN. Input data are variety loading and output data are r_{eq}, x_{eq} and P_{max}. Table 2 shows the calculation results based on losses concept compared with RBFNN training results for P_{max}. The calcution results based on losses concept compared with RBFNN training results for r_{eq}, x_{eq} and P_{max} are shown in Figure 7, Figure 8 and Figure 9, respectively.

Table 2
Comparison between calculation results based on losses concept and RBFNN training results

No	Loading (MW)	Computation Results (MW)	RBFNN Training Results (MW)
1	11500	652.4989497	652,498949700000
2	11700	638.8104266	638,810426600000
3	11800	632.1822908	632,182290800000
4	11900	625.6934648	625,693464800000
5	12000	619.3405428	619,340542800000
6	12588	595,1294518	595,129451800000
7	12535	593,9498319	593,949831900000
8	12199	613,3813059	613,381305900000
9	12550	593,3139323	593,313932300000
10	13096	567,969285	567,969285000000
11	13108	564,5329447	564,532944700000
12	12863	578,7680179	578,768017900000
13	12229	618,2484443	618,248444300000
14	11457	654,6639656	654,663965600000
15	11000	702,8536434	702,853643400000
16	11100	691,8111511	691,811151100000
17	11200	676,4524705	676,452470500000
18	11300	666,7990814	666,799081400000
19	11400	659,5700152	659,570015200000

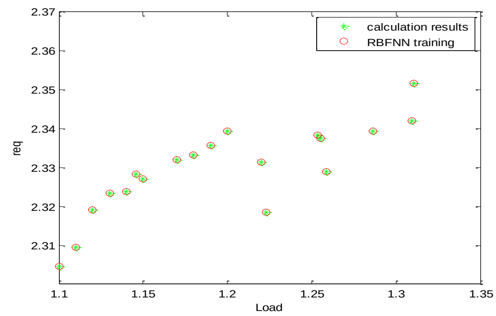

Figure 7: Calculation results compared with RBFNN training results for r_{eq}

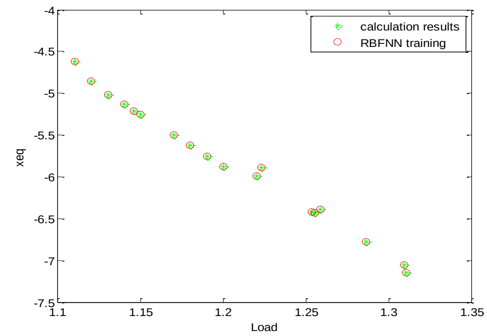

Figure 8: Calculation results compared with RBFNN training results for x_{eq}

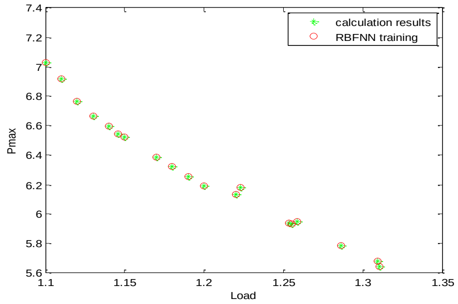

Figure 9: Calculation results compared with RBFNN training results for P_{max}

The calculation results compared with RBFNN testing results are shown in Figure 10 and Table 3.

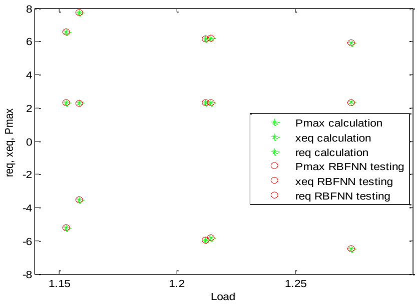

Figure 10: Calculation results compared with RBFNN testing results for r_{eq}, x_{eq} and P_{max}

Table 3
Comparison between calculation results based on losses concept and RBFNN testing results

No	Load (MW)	Computation Results (MW)	RBFNN Testing Results (MW)
1	11.586	776,0435604	776,043560400002
2	12.143	622,0615119	622,061511900001
3	12.122	615,4316063	615,431606300001
4	11.531	655,0963933	655,096393300000
5	12.737	590,8099048	590,809904800000

Figure 10 and Table 3 show that the calculation results based on the losses concept compared with RBFNN testing results lead to good performance.

Load flow analysis in ETAP simulation was used to validate the calculation results. The observed generator was turned on and others were turned off. Rated load increased gradually until it reached a state where if the loading value is raised again the load flow process becomes divergent. The generating value that is obtained before the load flow process divergent is the maximum limit of the generation which is a steady state stability limit of the generator.

The calculation results of P_{max} which is a steady state stability limit of observed generator unit using the proposed method compared with RBFNN testing results and ETAP simulation result can be seen in Table 4.

Table 4
Calculation results of P_{max} based on losses concept compared with ETAP simulation results

Load (MW)	Computation Results (MW)	RBFNN Testing Results (MW)	ETAP Simulation Results (MW)
11.586	776,0435604	776,043560400002	701,865
12.143	622,0615119	622,061511900001	632,62
12.122	615,4316063	615,431606300001	627,865
11.531	655,0963933	655,096393300000	664,866
12.737	590,8099048	590,809904800000	510,585

P_{max} calculation results obtained by the proposed method were not much different compared with the results obtained by the ETAP simulation. It can be concluded that, the method to change multimachine system into SMIB presented in this paper can be applied and determination of r_{eq} and x_{eq} value based on the network losses concept can be done. By using the proposed method, steady state stability limit of each generator in a multimachine system can be determined easily.

V. Conclusion

The method to change from the multimachine system to SMIB system presented in this paper is easy to be applied in power system with multimachine system interconnection. After the SMIB system is obtained, losses network value can be determine and then the equivalent impedance value can be calculated. Determination of the maximum generation, which is a generator steady state stability limit of units generator can be calculated after the network impedance is obtained.

RBFNN is applied to determine P_{max} of generator Saguling on variety of load demands given the great results. Therefore, the determination of the maximum generation limit of generator Saguling can be determined directly at any time change of the load demand.

The method to change multimachine system into SMIB presented in this paper can be applied and determination of req and xeq value based on the network losses concept can be done. By using the proposed method, steady state stability limit of each generator in a multimachine system can be determined easily. It will be very useful for guiding the operator in operating their generator safely.

Acknowledgement

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