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International **Review on Modelling and Simulations** (I.RE.MO.S.), Vol. 10, N. 2 ISSN 1974-9821 April 2017 Copyright © 2017 Praise Worthy Prize S.r.l. - All rights reserved <https://doi.org/10.15866/iremos.v10i2.11207> 112 112 112 Reactualization of **a Modified Single Machine to Infinite Bus** Model to Multimachine System Steady State Stability Analysis Studies Using Losses Network Concepts and **Radial Basis Function Neural Network (RBFNN)** Rusilawati^{1,2}, Adi Soeprijanto¹, Rony Seto Wibowo¹ Abstract – To analyze the stability of each generator, the multimachine system must be changed into a **Modified Single Machine to Infinite Bus (M-SMIB)** system.

This paper proposes a method to change the multimachine system into a M-SMIB system with an equivalent impedance and an equivalent load by determining the contribution of each generator to a loading value using a simple technique. After the M-SMIB system is obtained, a steady-state stability analysis can be performed on each generator unit. In this paper, the maximum generation value which is the generator steady state stability limit, is determined. The Radial Basis Function Neural Network (RBFNN) is applied to determine the range area of generator steady state stability with the variable load to observe the influence of load variation in the generator steady state stability area.

Thus, the area of safe operation of the generator can be directly observed without causing instability of the system. Therefore, the steady state stability limits of each generator unit can be directly determined every time there is a change of loading and recognize the operation limit of each generator during disturbances occurring on the bus. This method will be applied to a 4-bus IEEE system with 2 generators. Copyright © 2017 Praise Worthy Prize S.r.l. - All rights reserved.

Keywords: Generator Steady State Stability Limit, Modified Single Machine to Infinite Bus (M-SMIB) System, Radial Basis Function Neural Network (RBFNN) Nomenclature dQ / dV Stability index E Internal voltage at generator terminal I Generated current I' A set of all bus generators in the system I^* I conjugate j The adjacent bus M Generating power k Bus generator L NGDF-s of the line $L_{ip,k}$ Generator k contribution to the power flow in the line i_p $L_{rj,k}$ NGDF of the line r_j and for the generator at the bus k M_i Power generated at bus i $M_{i,k}$ The degree of the bus i is supplied by each generator in the system $-M_{ip}$ Power flow to bus i from bus p NGDF Nodal Generation Distribution Factor P Active power PL Active power losses P_{max} Generator steady state stability limit Q Reactive power QL Reactive power losses r A source bus r_{eq} Equivalent resistance S_{in} Power generation complex V Voltage at infinite bus V_i Voltage at bus i X Transferred reactance between E and V X_d Generator reactance x_{eq} Equivalent reactance \mathcal{I}_i A set of lines that is supplied by bus i \mathcal{I}_i A set consisting of all lines supplying bus i .

Introduction The steady state stability limit of the power system is represented by the steady state operating conditions where the power system is still stable, but small changes in the operating conditions will cause the system to lose its stability [1]. The multimachine system instability can be caused by a failure in the distribution of large power between two areas, for example due to an increase in load demand or to a lack of generation to meet load demands [2]. Several techniques to analyze the steady state stability of multimachine system have been employed to analyze the steady state matrix using eigenvalues and Paul Dimo approach, using the stability index of dQ / dV to determine whether the current condition is stable or not [3]. The obtained value determined with the previous techniques is the steady state stability limit for the Rusilawati, Adi Soeprijanto, Rony Seto Wibowo Copyright © 2017 Praise Worthy Prize S.r.l.

- All rights reserved International Review on Modelling and Simulations, Vol. 10, N. 2 113 entire system and not the steady state stability limit of each generator unit. To analyze the stability of each generator unit, the multimachine system must be changed into a Single Machine to Infinite Bus system by collecting all the loads into the load centers of the infinite bus. A power system net reduction has been done in [4]- [10], which means reducing the number of buses by collecting the same buses type into one group even if the SMIB system is not formed.

The determination of the equivalent impedance value for SMIB system using losses concept and determination of steady state stability limits on the SMIB system has been performed in [11]-[23]. Nevertheless, the way to change the multimachine system into a SMIB system is not given. This paper presents a simple method to change the multimachine system into a Modified Single Machine to Infinite Bus (M-SMIB) system

with an equivalent impedance and an equivalent load.

The multimachine system is converted into a M-SMIB system by determining the contribution of each generator at a certain load value [24]-[32]. The determination of the maximum generation, which is the generator steady state stability limit, can be done after the impedance of the network is obtained and the multimachine system is converted into the M-SMIB system. The determination of the generator security area using the robust system by considering the uncertainty of the loading value has been carried out in [37].

In this research, the Radial Basis Function Neural Network (RBFNN), which is one of the artificial neural network models, was applied to determine the range area of the generator steady state stability limit at varying loads. RBF is chosen because its architecture is more simple than perceptron to keep the main properties of the general estimation function. RBFNN is able to provide better forecasting accuracy in the majority of testing data [33]-[36]. Thus, the determination of the steady state stability limit of each generator unit can be directly determined at any time there is a load change and the area where the generator can safely operate without causing instability to system can be directly observed. II. Problem Formulation II.1.

Steady State Stability Limit of Electric Power System The electric power system is a system that consists in electric power components connected by a transmission net used to provide, supply and transmit electric power to consumers [38]. The electric power system interconnection between generations is shown in Fig. 1. In real life, electric power systems analysis is very complicated and complex. It is basically divided into three parts which are the generator system, transmission, and load. The main purpose of the interconnected system is to maintain the continuity and availability of electric power of the continuously increasing load demand.

Besides it is aimed at reaching the balance between provided power and needed power when operating in an electric power system. Fig. 1. Electric power system interconnection Instability in multimachine systems can be caused by a failure in the transmission of high power between two areas, for instance due to the increase in load demand or the lack of a generator to meet the load demand [2]. The steady state stability limit of the electric power system is a condition where power system is in a stable condition but a minor change of the operation condition will make the system lose its stability [1]. II.2.

Determining the Generator Contribution on Load and Power Flow In order to transform the multimachine system into the M-SMIB system, the important factor is to determine

which generators supply the load, what is the contribution of each generator to the load and what is each generator's contribution to system losses [24]-[32]. The method to determine the generator contribution on load bus can be based on precise generating distribution factors. The method used is the node method, which determines each generator contribution on power flow (the nodal generation distribution factor (NGDF-s)) [28]. NGDF-s are first calculated for the line connected to source buses.

If bus r is a source bus, then for all the lines connected to the adjacent bus j , is used: $M_{rj} = 0$ (1) with: $M =$ active power (P) and reactive power (Q): $M \in \{P, Q\}$ (2) NGDF-s for this line equals to 1 for the generator that supplies this line and 0 for all the other generators: $L_{rj,k} = 1$; $= 0$; ? (3) with: $L_{rj,k}$ used for NGDF of the line rj and for the generator in the bus k . Rusilawati, Adi Soeprijanto, Rony Seto Wibowo Copyright © 2017 Praise Worthy Prize S.r.l. - All rights reserved International Review on Modelling and Simulations, Vol. 10, N. 2 114 Following the rule explained above, the NGDF-s for all lines supplied by a source bus can be determined.

The NGDF-s for all lines which are not directly supplied by the source bus can be calculated later. If i is a set of all the lines supplied by bus i , $L_{ip,k}$ for all lines from the set i are calculated in advance. For the bus i , it can be calculated how much the bus is supplied by each generator in the system using the following equation: $M_{i,k} = -M_{ip} + M_{ik}$ (4) with: M_i = power generated at bus i , $-M_{ip}$ = power flow to bus i from bus p , $L_{ip,k}$ = generator k contribution to the power flow in the line ip , i = a set consisting of all lines supplying bus i , for instance, the line where $M_{ip} < 0$.

Furthermore, the principle of proportional division is used and the NGDF-s of all the lines supplied by bus i is: $L_{ij} = \frac{M_{ij}}{M_i}$ (5) for all $ij \in i$, with: I' = a set of all bus generators in the system This calculation must be done on all buses in the power system generated by NGDF-s for all lines. These factors can express the contribution of each generator in the power flow on the selected line. II.3. Radial Basis Function Neural Network (RBFNN) The Radial Basis Function Neural Network (RBFNN) is one of the artificial neural network models. RBF is a function commonly used in the regression.

Besides, the RBFNN can handle nonlinear data which tend to be similar to the conditions in the real world. RBFNN has only one nonlinear hidden layer and linear output to accelerate computation. Convergently, it is faster than the Multi-Layer Perceptron which has more than one hidden layer. The RBF function is applied to multi-layer perceptron neural networks called RBFNN [33]-[36]. RBFNNs are able to provide forecast accuracy better than the majority of testing data.

The activation function mostly used on another NN algorithm is the sigmoid function, while RBFNN uses the basic function in the hidden layer and linear function on output layer. This particular characteristic of RBFNN causes RBFNN work faster than other NN algorithms [33]. Fig. 2 shows the RBFNN architecture. The RBFNN model consists of three layers: the input layer, the hidden layer, and the output layer. The input layer accepts input vector x , then it is taken to the hidden layer, which will process input data as a nonlinear activation function. The output from hidden layer will be processed further in output layer as linear data [34]. Fig. 2.

RBFNN architecture III. Proposed Method III.1. Reduction of Multimachine System into M-SMIB System and Determination of Generator Steady State Stability Limit The electrical power system is a large system with a multi-generator (multimachine). It is very difficult to perform generator stability analysis on multimachine systems. Thus, the multimachine system must be previously changed into a Modified Single Machine to Infinite Bus (M-SMIB) system. Multimachine system is converted into equivalent impedance and equivalent load, as shown in Fig. 3. Fig. 3.

Modified Single Machine to Infinite Bus (M-SMIB) system The procedure to change the multimachine system into the M-SMIB system and the determination of maximum generation (P_{max}) which is a steady state stability limit of each generator can be explained as follows: 1. Set the loading value data, run the power flow program. 2. Next, calculate the contribution value of each generator unit on the loading value using equation (1) - (5). 3. Obtain the value of active power (P), reactive power (Q), active power losses (PL) and reactive power losses (QL). 4.

Calculate the current value I of the observed generator that is equal to the equivalent current using the following equation [39]-[40]: $I = \frac{P + jQ}{V_i}$ (6) Rusilawati, Adi Soeprijanto, Rony Seto Wibowo Copyright © 2017 Praise Worthy Prize S.r.l. - All rights reserved International Review on Modelling and Simulations, Vol. 10, N. 2 115 with: $I^* = I$ conjugate, $S_{in} = P + jQ$ = power generation complex, V_i = Voltage at bus i 5. Calculate r_{eq} and x_{eq} values using the losses concept as shown in the following equation: $PL = I^2 r_{eq}$ (7) and: $QL = I^2 x_{eq}$ (8) with: PL = active power losses, QL = reactive power losses, r_{eq} = equivalent resistance, x_{eq} = equivalent reactance. 6.

Calculate E using equation: $E = V + I X$ (9) with: E = internal voltage at generator terminal, V = voltage at infinite bus, I = generated current, X = transferred reactance between E and V : $X = X_d' + x_{eq}$ (10) with: X_d' = generator reactance, x_{eq} = equivalent reactance. 7. Determine the maximum generation of observed generator which is generator steady state stability limit using the following equation: $\max E V P X$ (11) with: P_{max} = generator steady state stability limit. 8. Repeat the above procedure for an

observed generator with variable loading values until acquiring some loading data which can be used as training data on RBFNN. III.2.

The RBFNN Training and Testing for Determining The Maximum Power of Each Unit Generator The data obtained in the procedure are described in Section III.1 and used for the RBFNN training data. Input data is a variation of loading data and outputs are req, xeq and Pmax. the RBFNN architecture used in this paper is shown in Fig. 4. The maximum generation value obtained is the generator steady state stability limit. After training, testing will be done on RBFNN to prove the accuracy of the obtained results. Fig. 4. RBFNN architecture on paper III.3.

Determination of Generator Steady State Stability Range Area using RBFNN After RBFNN is applied to determine the maximum generation, which is the steady state stability limit of each unit generator with varying loading values, it will be conducted to determine the generator steady state stability range area. The maximum generation value range obtained using RBFNN with varying loading values is a generator steady state stability limit range area. IV. Simulation and Analysis The simulation was performed on a 4-bus IEEE system with 2 generators, as shown in Fig. 5. Fig. 5.

4 Bus IEEE System The procedure for changing the multimachine system into a M-SMIB system and the determination of the maximum generation (Pmax) which is the steady state stability limit of each generator can be explained as follows: 1. The calculation results of NGDFs at each line [28] for the 4-bus IEEE system with 2 generators at a loading value of 500 MW can be seen in Table I and the contribution of each generator unit on each load is shown in Table II. Rusilawati, Adi Soeprijanto, Rony Seto Wibowo Copyright © 2017 Praise Worthy Prize S.r.l. - All rights reserved International Review on Modelling and Simulations, Vol. 10, N.

2 116 TABLE I THE NGDF-S VALUE AT EACH LINE FOR 4 BUS IEEE SYSTEM AT LOADING VALUE 500 MW Line Generator #1 Generator #2 1-2 1,000 0,000 1-3 1,000 0,000 4-2 0,226 0,774 4-3 0,485 0,515 TABLE II THE CONTRIBUTION OF EACH GENERATOR UNIT ON EACH LOAD FOR 4 BUS IEEE SYSTEM AT LOADING VALUE 500 MW Load (Bus) Generator #1 (%) Generator #2 (%) 1 100 0 2 22,6 77,4 3 48,5 51,5 4 0 100 2. The loading value is adjusted to the contribution of each generator so that the loading value obtained for generator 1 is 185.55 MW and the loading value for generator 2 is 314.45 MW. 3. The obtained values are active power (P) = 186.47 MW, reactive power (Q) = 87.3 MVAR, active power losses (PL)= 1.048 MW and reactive power losses (QL) = 5.24 MVAR, respectively. 4. The current value of the observed generator is I = 1.647719 pu. 5. The calculation results of req = 0.003860 and xeq = 0.019300 pu. 6. The calculation result of the maximum generation which is generator 1 steady state stability limit on

loading value 500 MW is 197.8921 MW. 7.

Repeat the procedure to determine generator 2 steady state stability limit, and obtain the maximum generation, generator 2 steady state stability limit on loading value 500 MW is 302.1948 MW. 9. Repeat the above procedure for the observed generator with variable loading values until getting some loading data to be used as RBFNN training data. The calculation results of req, xeq and Pmax are compared to RBFNN training results for Generator 1, as shown in Fig. 6, Fig. 7 and Fig. 8, respectively.

The calculation results of req, xeq and Pmax are compared to RBFNN training results for Generator 2, as shown in Fig. 9, Fig. 10 and Fig. 11, respectively. From Fig. 6 to Fig. 11 above it can be seen that the comparison of the calculating and RBFNN training of req, xeq and Pmax for Generator 1 and Generator 2 showed similar results. Furthermore, RBFNN testing must be done. The calculation results of req, xeq and Pmax are compared to RBFNN testing results for Generator 1, as shown in Fig. 12, Fig. 13 and Fig. 14, respectively.

The calculation results of req, xeq and Pmax are compared to RBFNN testing results for Generator 2, as shown in Fig. 15, Fig. 16 and Fig. 17, respectively. Fig. 12 to Fig. 17 show the calculation results of req, xeq and Pmax compared to RBFNN testing results for Generator 1 and Generator 2, and showed similar results, which means that it gave very positive results. Fig. 6. The calculation results of req is compared with RBFNN training results for generator 1 Fig. 7. The calculation results of xeq is compared with RBFNN training results for generator 1 Fig. 8.

The calculation results of Pmax compare with RBFNN training results for generator 1 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 0 1 2 3 4 5 6 Pload r equivalent Calculation Results RBFNN Training 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 0 0.5 1 1.5 2 2.5 3 Pload x equivalent Calculation Results RBFNN Training 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 0.5 1 1.5 2 2.5 3 3.5 4 4.5 Pload Pmax Calculation Results RBFNN Training Rusilawati, Adi Soeprijanto, Rony Seto Wibowo Copyright © 2017 Praise Worthy Prize S.r.l. - All rights reserved International Review on Modelling and Simulations, Vol. 10, N. 2 117 Fig. 9. The calculation results of req is compared with RBFNN training results for generator 2 Fig. 10.

The calculation results of xeq is compared with RBFNN training results for generator 2 Fig. 11. The calculation results of Pmax is compared with RBFNN training results for generator 2 Therefore, RBFNN can be used to directly determine req, xeq and Pmax values which represent the generator steady-state stability limit any time the loading value of the power system changes. The boundaries of the steady state stability limit area for Generator 1 and Generator 2 with varying loading values can be seen in Fig. 18.

Fig. 12.

The calculation results of r_{eq} is compared with RBFNN testing for Generator 1 Fig. 13. The calculation results of x_{eq} is compared with RBFNN testing for Generator 1 Fig. 14. The calculation results of P_{max} is compared with RBFNN testing for Generator 1 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 0 1 2 3 4 5 6 Pload r equivalent Calculation Results RBFNN Training 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 0 0.5 1 1.5 2 2.5 3 Pload x equivalent Calculation Results RBFNN Training 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 2 2.5 3 3.5 Pload P_{max} Calculation Results RBFNN Training 4.5 4.6 4.7 4.8 4.9 5 5.1 2.2 2.4 2.6 2.8 3 3.2 3.4 3.6 3.8 4 4.2

Pload r equivalent Calculation Results RBFNN Testing 4.5 4.6 4.7 4.8 4.9 5 5.1 1 1.2 1.4 1.6 1.8 2 2.2 2.4 Pload x equivalent Calculation Results RBFNN Testing 4.5 4.6 4.7 4.8 4.9 5 5.1 1.4 1.5 1.6 1.7 1.8 1.9 2 2.1 Pload P_{max} Calculation Results RBFNN Testing Rusilawati, Adi Soeprijanto, Rony Seto Wibowo Copyright © 2017 Praise Worthy Prize S.r.l. - All rights reserved [International Review on Modelling and Simulations](#), Vol. 10, N. 2 118 Fig. 15. The calculation results of r_{eq} is compared with RBFNN testing for Generator 2 Fig. 16. The calculation results of x_{eq} is compared with RBFNN testing for Generator 2 Fig. 17.

The calculation results of P_{max} is compared with RBFNN testing for Generator 2 Fig. 18 shows that Generator 1 tends to increase with the rising of the generation loading value, whereas Generator 2 tends to decrease. The generation value variation of Generator 1 is wider when compared to the generation value variation of Generator 2. It can be seen that the Generator 1 supplies more power for high loads and generator 2 tends to supply power at its maximum value, which is [the steady state stability limit of](#) Generator 2.

The conclusion is that the Generator [Bus 1 is the swing bus](#) of the [4-bus IEEE system with 2 generators](#). 0 100 200 300 400 500 328,05 348,55 358,72 364,50 383,82 405,00 410,06 414,48 427,78 440,35 450,00 457,50 471,26 500,00 507,36 518,09 538,58 551,20 596,97 603,07 609,61 625,00 648,25 670,57 717,19 Variasi Pembangkitan Gen1 Variasi Pembangkitan Gen2 MinGen1 MaxGen1 MinGen2 MaxGen2 Fig. 18. The Boundaries of [Steady State Stability Limit](#) Area For Generator 1 and Generator 2 with Varying Load Values V.

Conclusion [To analyze the stability of each generator unit, the multimachine system must be changed into a Single Machine to Infinite Bus system.](#) The way to change the [multimachine system into SMIB system](#) is not given in the other approaches. The simplest [method to change the](#) interconnection system consisting in many machines (multimachine) into the [Modified Single Machine to Infinite Bus \(M-SMIB\) system](#) has been described [in this paper.](#) The contribution of each generator unit to the system at

the loading value is determined in the multimachine system, then the M-SMIB system is formed with a generator connected to an infinite bus through equivalent impedance and equivalent load in the load center. Having formed the M-SMIB system, the maximum generation value can be easily determined, which is the generator steady state stability limit.

The application of RBFNN gives good results, as proved in this paper, therefore the steady state stability limit can be determined with varying loading values and the boundaries of generator steady state stability limit area can be determined. Thus, the steady state stability limit of each unit generator can be directly determined any time the loading value changes. Besides, with M-SMIB, the determination of the steady state stability limit as it has been done in this paper, can also be performed through the transient stability analysis and the dynamic stability analysis of each unit generator.

Thus, it is possible to know which is the troubled generator unit during disturbances in the interconnected multimachine system, and the troubled generator can be disconnected so that the disturbances do not extend to other generators, which could cause the system blackout. References [1] S. C. Savulescu (ed.), *Real-Time Stability in Power Systems*, (Power Electronics and Power Systems, Springer International Publishing – Switzerland, 2014). [2] Savu C. Savulescu, Overview of Key Stability Concepts Applied
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