Determination of Steady State Stability Margin Using Extreme Learning Machine

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Abstract: - Power systems have increased in size and complexity due to rapid growth of widespread interconnection. This situation will make power system operated closer to steady-state stability limit (SSSL) resulting in higher probability voltage instability or voltage collapse. This paper presents SSSL assessment in power system using Extreme Learning Machine (ELM) model based on REI-Dimo method. The equivalent REI-Dimo is used to determine SSSL index of the power systems. Then, the result of REI-Dimo will be taught on ELM method via online. The results of ELM will compared with Artificial Neural Network (ANN) method. Studies were carried out on a Java-Bali 500kV system. The simulation showed that the proposed method could accurately predict the proximity to SSSL in power system. The proposed method was computationally efficient and suitable for online monitoring of steady-state stability condition in the power systems.

1 Introduction

Load growth without a corresponding increase in transmission capacity has brought power systems operate near to steady state stability limit (SSSL). When a power system approaches the SSSL, the voltage of some buses reduces rapidly for small increments in load and the controls or operators may not able to prevent the voltage decay or collapse. Voltage collapse has become an increasing threat to power system security and reliability. To operate the system with an adequate security margin, it is essential to estimate the voltage stability margin corresponding to the given operating point. The main problem here is that the maximum permissible loading of the transmission system is not a fixed quantity. It depends on various factors such as network topology, availability of reactive power support, generation and load patterns etc. All these factors continuously vary with time. Voltage magnitude alone cannot be used as an indicator of instability [1-3].

The steady-state stability limit (SSSL) of a power system is "a steady-state operating condition for which the power system is steady-state stable but an arbitrarily small change in any of the operating quantities in an unfavorable direction causes the power system to loose the stability". An earlier definition refers to this concept as "the stability of the system under the conditions of gradually or relatively slow changes in the load". Voltage collapse, units getting out of synchronism, and instability caused by self amplifying small-signal oscillations are all forms of steady-state instability [3].

Empirically, the risk of steady-state instability is associated with low real or reactive power reserves, low voltage levels, and large bus voltage variations for small load or generated power changes. Recurring "temporary faults", i.e. where breakers trip without apparent reason and which is disconnected by a protection without being able to identify the fault, might also be an indication of steady-state instability. Breaker trips can happen when loads increase due to "balancing rotors" of generators that are operated near instability trip and then get back in synchronism[1-5].

Equivalent REI (Radial, Equivalent and independent) has also been used to speed up and simplify the complex computational algorithms. For example, the rigorous solution of the steady-state stability problem is predicated on detailed machine model and entails an alternate sequence of load flow and eigenvalues calculating until the point of instability is found. However, determining eigenvalues for successively deteriorated load-flow cases is computationally intensive and has the

inconvenience that load-flow may not converge near the instability. The use of equivalent in conjunction with appropriate simplifying assumptions is the only way to overcome such difficulties and Dimo's method has been successfully implemented and is currently used in several SCADA/EMS installations to compute the system load ability limits in real-time and to continuously monitor the distance to instability [6]-[7].

A number of special algorithms have been proposed in the literature for steady state stability. However, these methods require large computations and are not efficient enough for on-line or real-time stability assessment. For real-time applications there is a need tools which can quickly detect the point collapse of system and to provide guidance to steer the system away from a developing voltage collapse.

Recently, there has been considerable interest in the application of Extreme Learning Machine (ELM) to power system. ELM has the ability to classify complex relationships properly. The relationships classified by ELM are highly non linear and often result from large mathematical models. Once trained, the ELM can classify new data much faster than it would be possible by solving the model analytically: An integrated based systems, ELM, and conventional power system solution methodologies have potential to provide real-time optimization and control of power system. [8]-[9].

This paper presents the application of ELM to provide fast indication of steady stability limit with the use of REI-Dimo result as training data. For online steady-state stability monitoring, it is essential to identify the maximum power of loading faster calculation so that the ELM method can be a alternative solution.

2 Research Method
2.1 REI-Dimo Equivalent

Many references that are available describe the approach to steady-state stability assessment developed by Paul Dimo, starting, of course, with the books and papers written by Dimo himself. ln order to avoid overlap with already-published material, in this section we just briefly discuss just the key aspects of the technique and emphasize the assumptions that provide computational speed while preserving precision and accuracy. The theoretically oriented reader is directed to review reference [1,6], in which the more subtle aspects of Dimo's methodology are addressed in detail, including the generalization of Dimo's formulation of the reactive-power steady-state stability criterion.

A power system consists of a linear sub-system, i.e., transmission lines, transformers, reactor, capacitors, and the bus-to-ground admittances to represent line charging and transformer taps; and a non-linear subsystem, i.e., generators, loads and synchronous condensers. Bus can divided into non-essential buses, which are to be eliminated, and essential buses, which are to be retained unchanged[1].

Figure 1, which meets the requirement that the generators be radially connected to a "nodal point" where the load is located. The topology of this network, in spite of its simplicity, reflects a typical radial network of short-circuit impedances (admittances) obtained after applying the short circuit current transformation [1].

The generators G_1 and G_2 the mechanical powers Pm_1 and Pm_2 equal the electrical MW generated powers, which are given by equations (1) and (2):

$$P_{ml} = P_1 = \frac{E_1 V}{X_1} \sin \delta_1 \qquad (1)$$

$$P_{m2} = P_2 = \frac{E_2 V}{X_2} \sin \delta_2 \qquad (2)$$

The generated real powers are entirely absorbed by the load Pload, as shown in equation (3):

$$P_{load} = \frac{E_1 V}{X_1} \sin d_1 + \frac{E_2 V}{X_2} \sin d_2 = const \qquad (3)$$

And the reactive power of the load Q_{load} is supplied by :

$$Q_{load} = \frac{V^2}{X_{load}} = \frac{E_1 V}{X_1} \cos \delta_1 - \frac{V^2}{X_1} + \frac{E_2 V}{X_2} \cos \delta_2 - \frac{V^2}{X_2} \qquad (4)$$

Let us now consider a perturbation ΔQ of reactive power injected into the load bus. From(1),(2),(3), and (4) and with $\Delta P_{ml} = 0$, $\Delta P_{m2} = 0$, $\Delta P_{load} = 0$, as well as $\partial Q_{load}/\partial d_1 = 0$ and $\partial Q_{load}/\partial \delta_2 = 0$ because Q_{load} is a function of V only, we obtain Jacobian matrix of the system [1]:

$$J = \begin{bmatrix} \dfrac{\partial P_1}{\partial V} & \dfrac{\partial P_1}{\partial \delta_1} & 0 \\[2ex] \dfrac{\partial (P_1 + P_2)}{\partial V} & \dfrac{\partial (P_1 + P_2)}{\partial \delta_1} & \dfrac{\partial (P_1 + P_2)}{\partial \delta_2} \\[2ex] \dfrac{\partial (Q_1 + Q_2 - Q_{load})}{\partial V} & \dfrac{\partial (Q_1 + Q_2)}{\partial \delta_1} & \dfrac{\partial (Q_1 + Q_2)}{\partial \delta_2} \end{bmatrix} \qquad (5)$$

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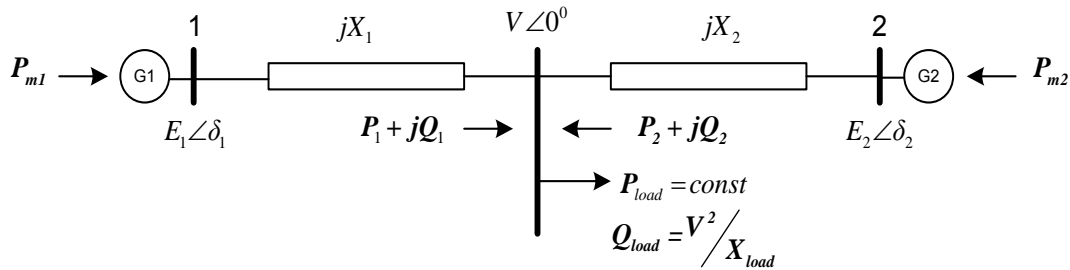
Fig.1 Radial network of generators connected to the nodal point

Then, we obtain the determinant D of Jacobian matrix:

$$D = (I_1 \cos\delta_1)(I_2 \cos\delta_2)V^2\left(\frac{I_1}{\cos\delta_1} + \frac{I_2}{\cos\delta_2} - 2YV\right) \quad (6)$$

The solution will get if, and only if, D≠0, in which case we obtain

$$\frac{d\Delta Q}{dV} = \frac{I_1}{\cos\delta_1} + \frac{I_2}{\cos\delta_2} - 2YV \quad (7)$$

Paul Dimo has shown that, for system of 1,..., m generators and synchronous condenser connected radially to a single-load bus (either actual or equivalent) through the admittance $Y_1,...,Y_i,...,Y_6$, the derivative can be computed with formula [1]:

$$\frac{d\Delta Q}{dV} = \sum_m \frac{Y_m E_m}{\cos d_m} - 2\left(\sum_m Y_m + Y_{load}\right)V \quad (8)$$

in which:

E_m = internal voltages of the machines (assumed to remain constant, unaffected by small adjustments made under steady-state stability conditions)

δ_m = internal angles of the machines with reference to the voltage V on the load bus (either fictitious or actual)

V = Voltage in the load center
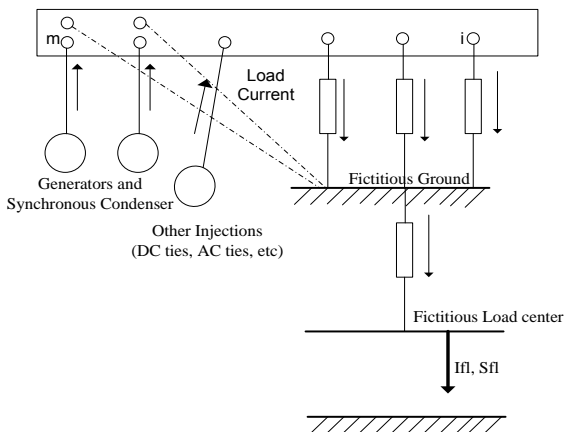
Y_{Load} = Load center admittance

Fig.2 Transition from the meshed power system network to radial scheme

to simplify, the formula in equation (8) will be separated be two component, such as :

$$D = \sum_m \frac{Y_m E_m}{\cos d_m} \quad \text{and} \quad E = 2\left(\sum_m Y_m + Y_{load}\right)V \quad (9)$$

To determine the pattern of economic relations to be represented on the stability index value, $d\Delta Q/dV$ is determined by changes in the parameters V and $\cos\delta_m$. The closer the distance load to the power plant that supplies the value $\cos\delta_m$, the greater it will be because the difference of angle bus that sends and receives is smaller. The result will be worth the value of D and E will be smaller and greater value. The small value of D and the greater value of E results in the distance to D = E or $d\Delta Q/dV$ =0 which becomes more distant. Therefore, this method can increase the steady-state stability limit [10].

2.2 Extreme Learning Machine for Steady State Stability

Conventional methods such as back-propagation (BP) and the method of Levenberg-Marquardt (LM) has been used extensively in training neural networks [17]. Although this algorithm is relatively slow in learning. A new learning method for single-hidden-layer feed forward neural-networks (SLFNs) the so-called extreme learning machine (ELM). In ELM, the input weights and hidden biases are randomly chosen. The output weights obtained using the Moore-Penrose (MP) generalized inverse. ELM has the capability in terms of speed and easier than traditional methods of gradient-based learning algorithms [14-17].

Compared to SVM (Super Vector Machine) and Back-Propagation, ELM has several advantages [15-19]:

1) ELM needs much less training time compared to popular BP and SVM.
2) The prediction accuracy of ELM is usually slightly better than BP and close to SVM.
3) Suitable for almost all nonlinear activation functions.

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In ELM, the input weights and hidden biases generated randomly. Furthermore, the nonlinear system has been transformed into a linear system:

$$H\beta = T$$

where as named in Huang et al. [15-19], $H=\{h_{ij}\}$ ($i=1,\ldots,N$ and $j=1,\ldots,K$) is hidden-layer output matrix, $\beta = [\beta_1, \beta_2, \ldots, \beta_K]^T$ is matrix of output weights and $T = [t_1, t_2, \ldots, t_N]^T$ is matrix of targets.
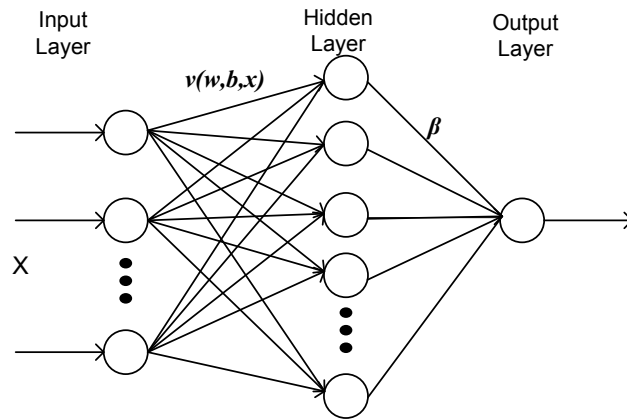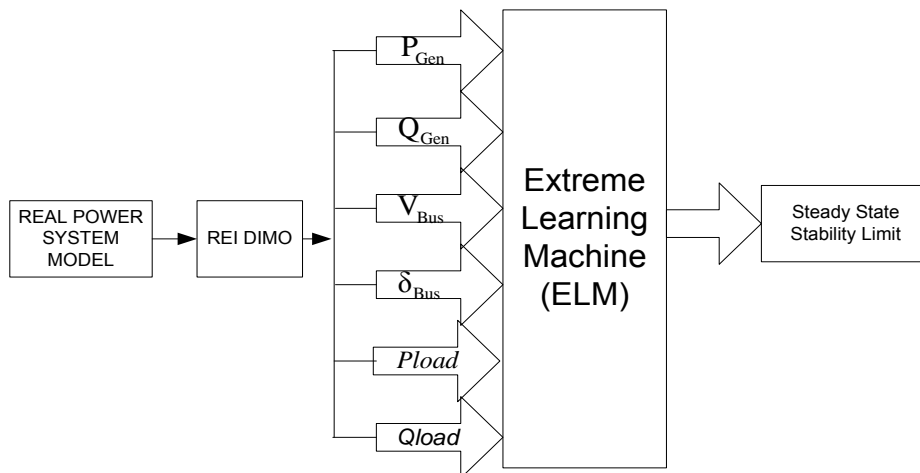
Fig.3 Structure of an SLF-NN

Fig.4 Scheme of research

In this paper, ELM is utilized to map the highly non-linear relationship between network voltage profile of load center from REI-Dimo Equivalent and the corresponding steady-state stability limit of power system. First, the simulation starts with running the power flow program for Java-Bali system. Then, by using REI- Dimo equivalent, the system will be reduced into simple network by reducing all load buses into a representative load center buses. Network voltage profile of reduced model is provided by REI-Dimo.

2.3 Structure of The Proposed Approach

Figure 4 shows the structure of the proposed approach. This approach consists of four main. Parts as follows:

1. Reducing the Java-Bali system be a simplify power system using REI- Dimo.
2. Determining the index steady-state stability limit using REI-Dimo
3. Changing the power in the load center to obtain the parameter of system such as: real power and reactive power generation, magnitude and phase of bus voltage, D and E constant, and SSSL index. All data obtained
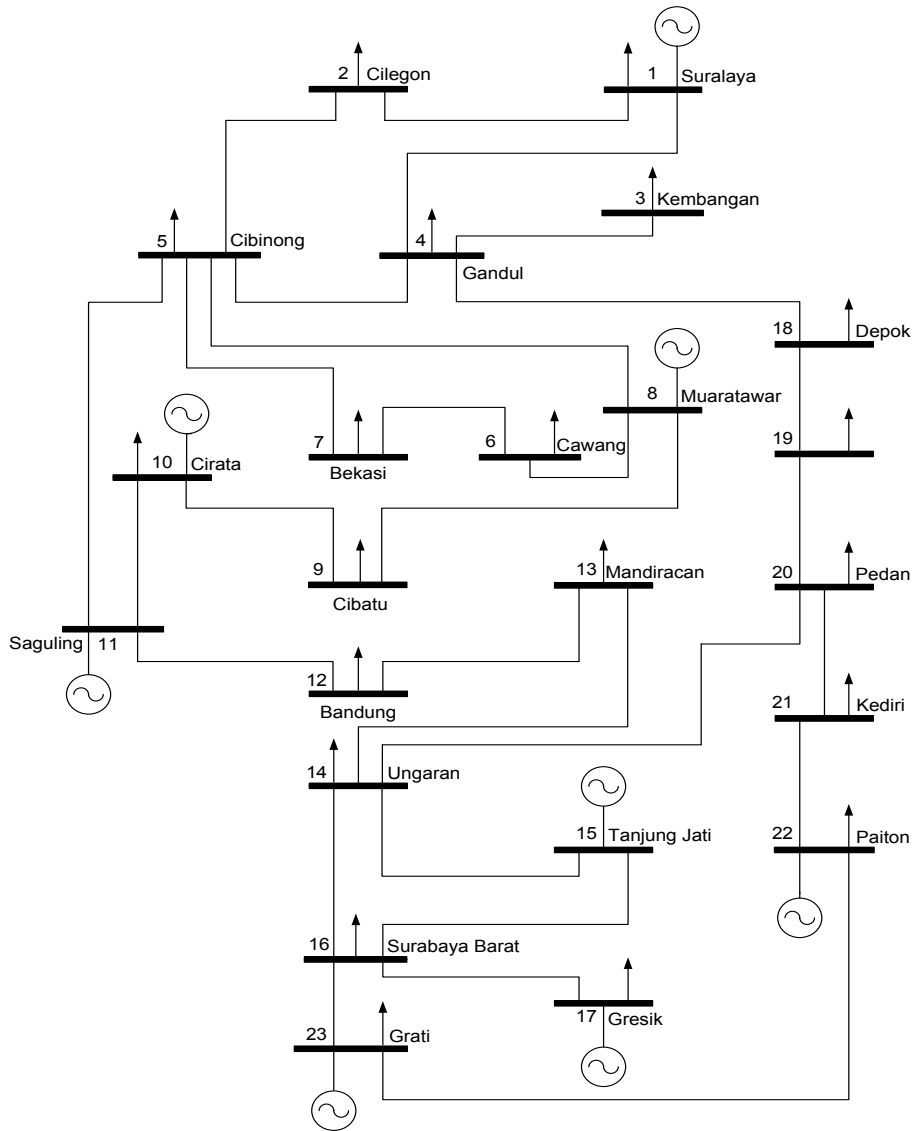
Fig.5 Single Line Diagram of 500 kV Java-Bali Power System

from steps (3) will be used to train, validate and test the ELM

4. Evaluating index SSSL using ELM

2.4 Test Power System

The Plant as the case for simulation is the 500 kV Java-Bali Power System as shown in Figure 5. The data of generator characteristics and cost, line impedances and an operating condition are shown at Tables 1-2.

3 Result And Analysis
3.1 REI-Dimo Equivalent for Java-Bali System

Figure 6, shows the single load REI equivalent of Java Bali system with 8 generator bus and one load centre. The Y bus of equivalent system after Gaussian Elimination and REI-Dimo parameter are given in Table 3 and Table 4.

The Java-Bali system changed into reduced model using REI-Dimo Method. Then using the equation (1), the steady state stability limit of Java-Bali system was obtained. Figure 7 shows the value of SSSL of Java-Bali system using REI-Dimo.

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Table 1 Line Data of 500 kV Java-Bali Power System

From Bus	To Bus	R (pu)	X(pu)	B (pu)
1	2	0,000626496	0,007008768	0
1	4	0.006513273	0.062576324	0.01197964
2	5	0.013133324	0.146925792	0.007061141
3	4	0.001513179	0.016928309	0
4	5	0.001246422	0.01197501	0
4	18	0.000694176	0.006669298	0
5	7	0.00444188	0.0426754	0
5	8	0.0062116	0.059678	0
5	11	0.00411138	0.04599504	0.008841946
6	7	0.001973648	0.01896184	0
6	8	0.0056256	0.054048	0
8	9	0.002822059	0.027112954	0
9	10	0.00273996	0.026324191	0
10	11	0.001474728	0.014168458	0
11	12	0.0019578	0.0219024	0
12	13	0.00699098	0.0671659	0.01285827
13	14	0.013478	0.12949	0.024789624
14	15	0.01353392	0.15140736	0.007276522
14	16	0.01579856	0.1517848	0.007264438
14	20	0.00903612	0.0868146	0
15	16	0.037539629	0.360662304	0.017261339
16	17	0.00139468	0.0133994	0
16	23	0.003986382	0.044596656	0
18	19	0.014056	0.157248	0.030228874
19	20	0.015311	0.171288	0.032927881
20	21	0.010291	0.115128	0.022131855
21	22	0.010291	0.115128	0.022131855
22	23	0.004435823	0.049624661	0.009539693

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Table 2 Operating Condition

| Bus | Load | | Generation | | Injected |
No.	MW	Mvar	MW	Mvar	Mvar
1	153	45	3332.176	988.564	0
2	703	227	0	0	0
3	760	261	0	0	0
4	544	181	0	0	0
5	697	215	0	0	0
6	760	181	0	0	0
7	646	170	0	0	0
8	0	0	1470	679.361	0
9	823	317	0	0	0
10	680	245	400	484.322	0
11	0	0	535	1043.085	0
12	590	351	0	0	0
13	397	136	0	0	0
14	329	363	0	0	0
15	0	0	830	361.87	0
16	862	317	0	0	0
17	210	91	810	608.616	0
18	0	0	0	0	0
19	277	17	0	0	0
20	524	244	0	0	-158
21	358	206	0	0	-193
22	839	272	2820	895.043	-96
23	130	193	198	395.97	0
Total	10282	4032	10395.18	5456.832	-447

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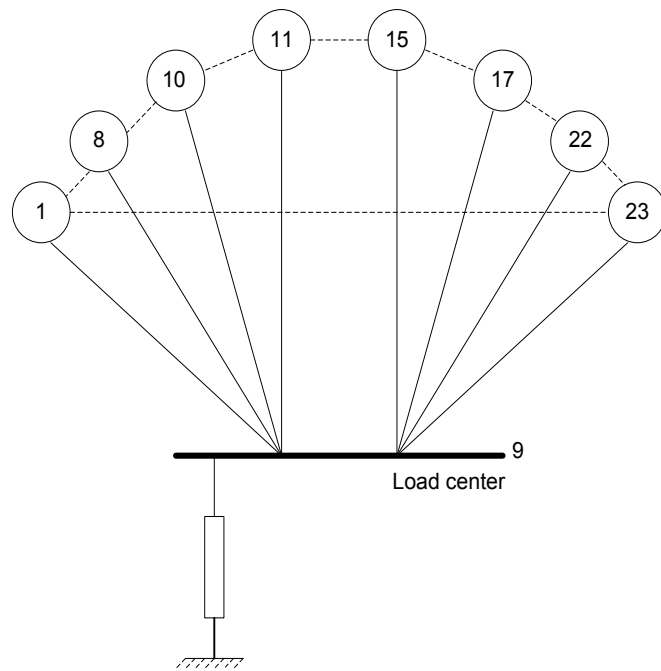Adi Soeprijanto, Ontoseno Penangsang

Fig.6 Single Load REI-Dimo of Java Bali System

Table 3 Y Bus of REI-Dimo Single Load Equivalent of Java Bali System

No Gen Bus	Bus 9 (Load Center)
1	-0.2296 - 2.7875i
8	-0.2282 - 2.5303i
10	-0.1732 - 1.8221i
11	0.0657 - 3.0665i
15	0.1065 - 0.6660i
17	0.0144 - 1.6252i
22	-0.0420 - 2.1648i
23	0.1672 - 0.6704i
9	0.3178 +15.2987i

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Table 4 REI-Dimo Parameter

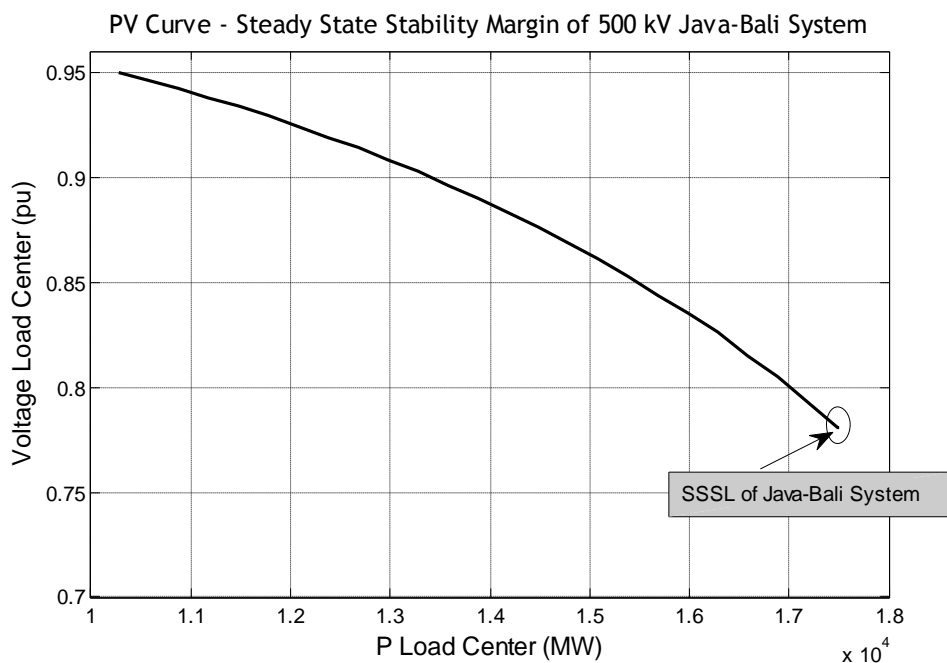| No Bus	Y re G (pu)	Y im B (pu)	REI MW	REI MVAr	V (pu)	V ang(^{0})
1	-.2296	-.7875	3314.2	988.564	1.02	0
8	-.2282	-.5303	1470	679.361	1	-6.241
10	-.1732	-.8221	400	484.322	1	-7.029
11	0.0657	-.0665	535	1043.09	1	-6.663
15	0.1065	-0.666	830	361.87	1	9.938
17	0.0144	-.6252	810	608.616	1	9.735
22	-0.042	-.1648	2820	895.043	1	14.303
23	0.1672	-.6704	198	395.97	1	11.751
9	-0.637	-.0341	10264	4032	0.94	-4.267

Fig.7 SSSL of Java-Bali System

3.2 Steady State Stability Using ELM for Java-Bali power system

All data determined from REI-Dimo such as: active power generation (P_{Gen}), reactive power generation (Q_{Gen}), voltage of all bus, active load power and reactive load power will be input data and Voltage in the load center ($V_{load\ center}$), index of SSSL by REI-Dimo equivalent will be output data for ELM method. All data will be trained with 500 hidden neurons, activation function 'sig'.

Using REI-Dimo method, maximum voltage obtained in the load center ($V_{load(max)}$) area is 0.781 (pu) and the SSSL is -1.2376. All data obtained from REI-Dimo will be trained to ELM. Training process

in ELM needs training time is 0.825 s but ANN needs time is 1.56 s , and obtained ($V_{load(max)}$) is 0.781 (pu) and SSSL is -1.2376 with the training error is 0%.

Table 5. A few data that obtained from REI-Dimo

P_1	Q_1	V_1	θ_1	. . .	P_{Load}	Q_{Load}	V_{Load}	θ_{Load}	D	E	SSSL Index
1657.62	898.594	1.02	0	. . .	10282	4032	0.95	-26.7	61.07	120.7	-59.657
1905.77	969.249	1.02	0	. . .	10582	4148.14	0.946	-28.88	61.26	120.6	-59.294
2149.54	1046	1.02	0	. . .	10882	4265.74	0.942	-31.08	61.46	120.4	-58.895
2388.82	1128.7	1.02	0	. . .	11182	4383.34	0.938	-33.3	61.69	120.1	-58.458
2623.35	1217.23	1.02	0	. . .	11482	4500.94	0.934	-35.53	61.94	119.9	-57.98
2852.83	1311.47	1.02	0	. . .	11782	4618.54	0.929	-37.78	62.22	119.7	-57.456
3076.92	1411.29	1.02	0	. . .	12082	4736.14	0.924	-40.05	62.53	119.4	-56.883

The proposed ELM architecture can have 50 input nodes and 2 output nodes and only one hidden layer is used. Sigmoid types of additive hidden nodes are used in this ELM.
In this paper, the performance of ELM will compare with Artificial Neural Network result. Fig.8 and Fig.9 shown the result of ELM training for both parameter, i.e. SSSL index and Voltage of Load Centre.
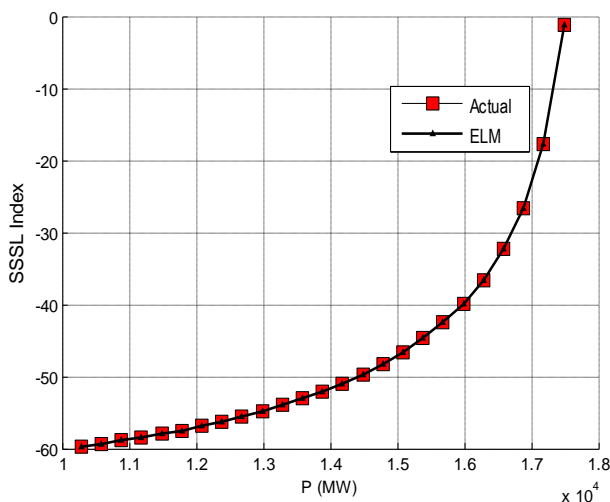

Figure 8. SSSL Index of ELM Training

After training and testing SSSELM, it is used in the working mode of the proposed algorithm as

shown in Table 6. In this mode, for any given operating point of power system by parameter measurement of bus voltages, voltage magnitudes and phase angles are extracted as input data to estimate SSSL by SSSELM.
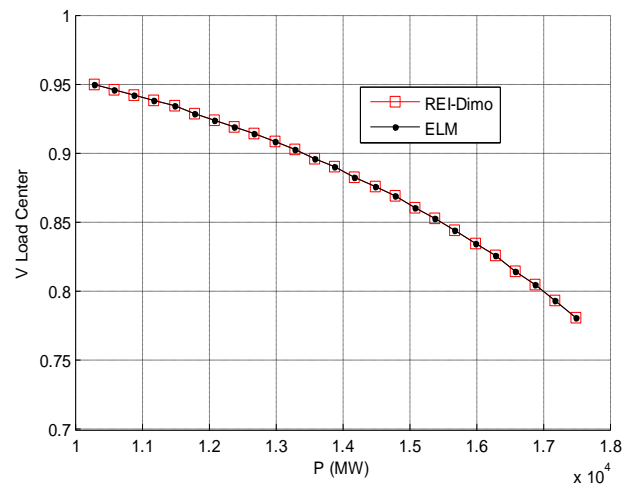

Figure 9. Voltage of Load Centre of ELM Training

As a case study, for an operating point with load center is 10640 MW and 4100.32 MVAR, the value of SSSL in Eq. (1) is taken as -59.4459 and two scenarios are studied in which all load center are supposed to be changed with 250 MW and 98 MVAR. Tables 7-8 show the result of load center change from 10460 MW to 11460 MW and 4100.32

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MVAR to 4492.32 MVAR and load center voltage change from 0.948 (pu) to 0.934 (pu). The overall error in the output values for the given example is less than 0.23% which will be acceptable and the. method has strong potential for steady state stability assessment. Tables 7 and 8 shows that the results of ELM method is more accurate than the ANN method. The table 7 shows that the maximum

testing absolute errors of SSSL for ELM method are: 0.06%, 0.17%, 0.1%, 0.23%, and 0.03%. Similarly, the maximum testing errors for ANN are: 0.45%, 0.32%, 0.24%, 0.19% and 0.57%. From these results, it can be seen that ELM has the less error level then ANN. The ELM is efficient for the prediction of the steady state stability limit in power system.
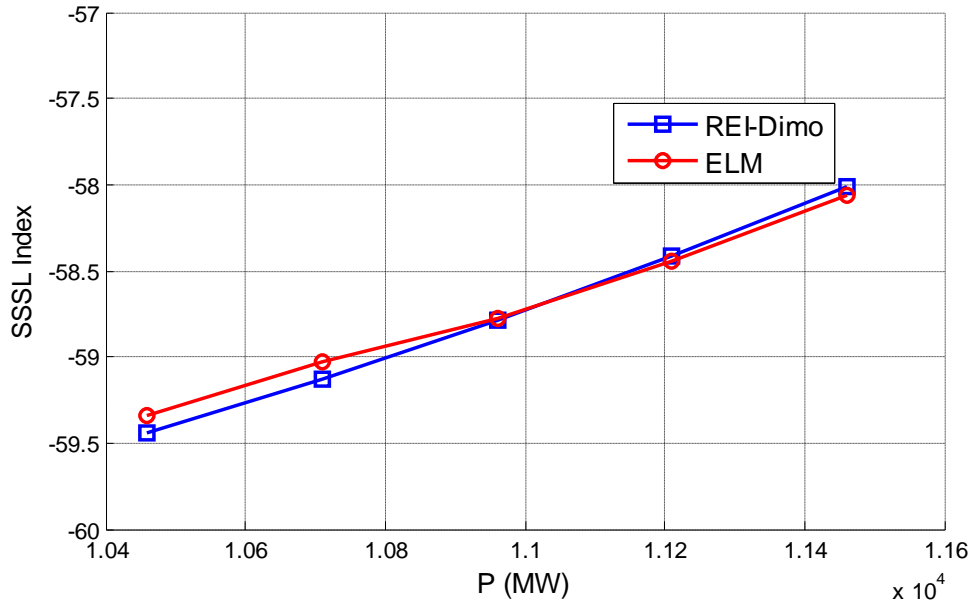

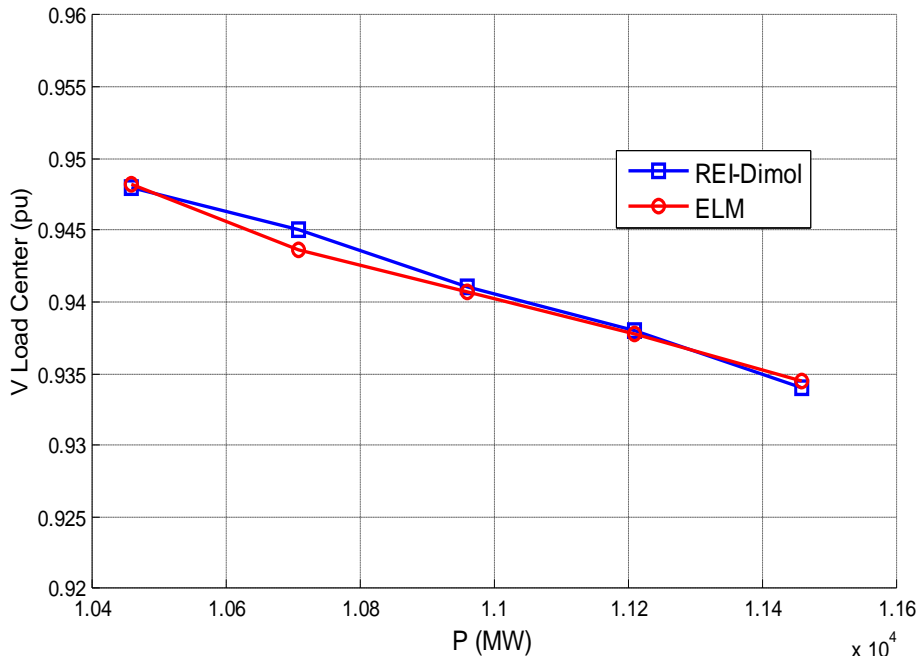Fig. 10 Comparison of SSSL index between the Actual Data and Testing Results of ELM

Fig.11 Comparison of Voltage of Load Centre between the Actual Data and Testing Results of ELM

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Table 6. A few of Data Testing from REI-Dimo

P Load Center (MW)	Q Load Center (MVAR)	V Load Center (pu)	θ Load Center (degree)	D	E	SSSL Index
10460	4100.32	0.948	-27.993	61.1773	120.6233	-59.4459
10710	4198.32	0.945	-29.819	61.342	120.47	-59.128
10960	4296.32	0.941	-31.656	61.521	120.31	-58.785
11210	4394.32	0.938	-33.504	61.714	120.13	-58.415
11460	4492.32	0.934	-35.365	61.924	119.94	-58.016

Table 7. The Comparison of Data Testing and Target for Index of SSSL

No. Data	Target	Testing		Error	
		ANN	ELM	ANN	ELM
1	-59.4459	-59.1794	-59.413	0.0045	0.0006
2	-59.128	-58.9366	-59.2311	0.0032	0.0017
3	-58.785	-58.6467	-58.7239	0.0024	0.001
4	-58.415	-58.3024	-58.2782	0.0019	0.0023
5	-58.016	-58.3482	-58.0314	0.0057	0.0003

Table 8. The Comparison of Data Testing and Target for Voltage of Load Center

No. Data	Target	Testing		Error	
		ANN	ELM	ANN	ELM
1	0.948	0.9457	0.9478	0.0024	0.0003
2	0.945	0.9428	0.9445	0.0023	0.0005
3	0.941	0.9398	0.9409	0.0013	0.0001
4	0.938	0.9366	0.9361	0.0015	0.0021
5	0.934	0.9364	0.9344	0.0025	0.0004

4 Conclusion

The estimated results obtained from ELM showed that this technique is able to predict the steady-state stability limit with a reasonable degree of accuracy and more accurate than ANN. Since ELMs had high computation rates, parallel distributed processing, fault tolerance, and adaptive capability, they were excellent alternatives for real-time application combined with REI-Dimo method. The result showed that REI-Dimo and ELM had overall error in the output values was less than 0.23% which would be acceptable and it meant that the SSSELM method had strong potential for steady-state stability assessment. And by considering the training time and accuracy of the networks, it could be safely concluded that SSSELM was well-suited for online steady-state stability assessment of power systems.
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