SUITABILITY OF AGGREGATION METHODS OF INDUCTION MOTOR MODELS FOR VOLTAGE STABILITY ANALYSIS

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ABSTRACT

This paper focusses on the aggregation of multiple induction motors (IM) connected in parallel on the same bus into a single equivalent model using aggregation based on transfomer equivalent-circuit (method 1) and on no-load and locked rotor (method 2).This has been necessitated by the strong effects that the non linear loads have on power system characteristics and therefore erroneous modeling of these devices continues to be an area of greater uncertainty. Though various methods of aggregations have been used, comparison on their suitablity and accuracy has not been extensively explored. Also investigated is the suitability of multi-band power system stabilizer (MB-PSS) on the aggregate motor under a fault.The accuracy of these methods is compared to dentify the most appropriate. Their performance is validated by evaluating the results obtained from individual and aggregate IM on IEEE 16 Bus test system. The results shows that method 2 is accurate than method 1 in identification of the motor parameters both under steady-state and under fault condition. The MB-PSS gives better damping of the oscillatory modes with method 2 than method 1. The former method can therefore be used for accurate analysis of voltage stability in a complex power system.

Keywords: *Aggregation Methods, Induction Motor, Voltage Stability, Power System Stabilizers.*

1.0 INTRODUCTION

Different aggregation methods have been applied for induction motor load representation by several researchers such as Hakim and Berg (1976); Franklin and Morelato (1994); Lem and Alden (1994); Pillay *et al.*, (1998); Bing *et al.*, (2010); Karakas *et al.*, (2009) and Abdalla, *et al.*, (2008) as a single equivalent model for ease and speed of power system analysis. However, comparison on the accuracy of these methods has not been meticulous. The induction motor modelling is paramount in the dynamic analysis of a power system since they contribute the biggest percentage of power system loads. In light of the above, they may cause delay during normal voltage recovery under fault conditions. Nevertheless, it is not practical to model every individual induction motors and especially large number of individual IM during the simulation studies because this can be highly time-consuming. Thus being the reason for aggregating several IM as a single equivalent model.

Therefore, aggregate models (single-unit equivalent models) are often employed. The accuracy of the results obtained with aggregate models depends in part on the assumptions made when deriving the aggregate motor and vary from method to method. Grouping criterion is also used to classify homogeneous motors as introduced by Pillay *et al.*, (1998). Further, the accuracy of the results depends on how good the models are and the number of components involved. It is well known that load modelling on system dynamics is crucial; however it is still a big challenge. This complexity is brought by the fact that load consists of various components with various characteristics, which have to be represented as an equivalent single model. Under fault condition, there is increased demand for reactive power by the IM due to reduced voltages and increased current. This high reactive power demand by the loads may cause the generators to lose their ability to act as a constant voltage source because of the field current limitation. For such a case the generator terminal voltage reduces gradually and may eventually cause the motor to stall.

The dynamic stability of a system can be improved by providing suitably tuned power system stabilizers (PSS) on selected generators to provide damping to power swings as implemented by Kundur (1994). Suitably tuned Power System Stabilizers will introduce a component of electrical torque in phase with generator rotor speed deviations resulting in damping of low frequency power oscillations in which the generators are participating. The PSS design is based on the linearized model of the power system. The input to stabilizer signal may be one of the locally available signals such as changes in rotor speed, rotor frequency, accelerating power or any other suitable signal. This stabilizing signal is compensated for phase and gain to result in adequate component of electrical torque that results in damping of rotor oscillations and thereby enhance power transmission and generation capabilities.

This paper compares the aggregation of the induction motor loads using method 1 and 2 respectively. These are achieved by simulating a group of induction motor by a single equivalent motor model and then analyzing their suitability on parameter identification of aggregate motor for voltage stability analysis. The test results demonstrate that, aggregation methods are of varying degrees of accuracy and are dependent on the assumptions made on derivation of the aggregate motor parameters. The Multi-Band PSS (MB-PSS) as applied by Muriithi *et al.*, (2011) is introduced to the generator of each aggregate motor model using the two methods of aggregation to identify the most suitable in maintaining the voltage stability of a power system subjected to a fault. The efficiency of the aggregate and individual IM is estimated using the IEEE 16 bus test system.

2.0 METHODOLOGY

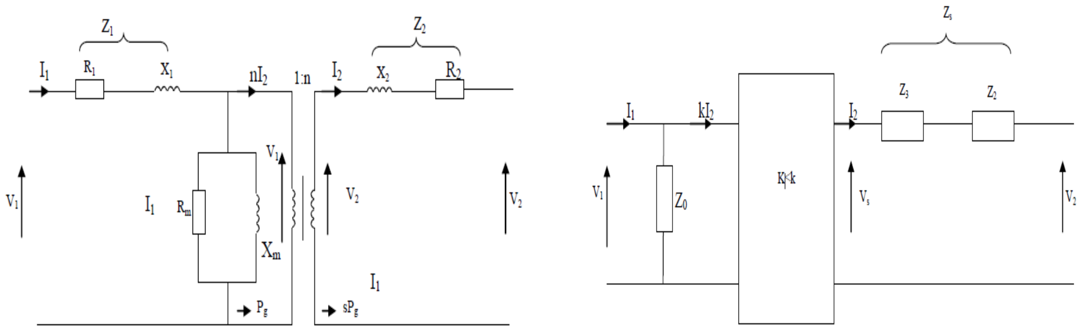
2.1 The Aggregation of Multiple Induction Motor Loads

Approximately 70 % of power system loads are induction motors and their aggregation for parameter identifications and transient stability study is critical. The simulation of large group of IM is extensive; therefore, to reduce the computation time, reduced order modelling is suggested to represent a group of motors with one or more aggregate motors. There are different aggregation methods proposed in the literature and their accuracy depends on the assumptions made and the complexity of the loads.

In this research, an aggregation method based on no-load and locked-rotor (method 2) proposed by Franklin and Morelato (1994) and transformer-type equivalents (method 1) proposed by Pillay *et al.*, (1998) are compared to identify their suitability in identification of IM parameters and voltage stability analysis. Aggregation without making some assumptions can prove to be an intricate venture and therefore, in this paper the following were assumptions made. All the motors are of the same type and are connected in parallel and at the same bus with no other load types. The output power for each motor is maintained for ease of comparison under the two aggregation methods of IM while the same number of poles is maintained. The two aggregation methods are discussed below:

2.1.1 Transformer-type equivalent circuit model (method 1)

It is a common practice to represent IM in a conventional equivalent circuit model as shown in Figure 1 (a); however, a transformer-type equivalent circuit model shown in Figure 1(b) have been used. The equations used by Pillay *et al.*, (1998) to obtain the aggregate motor model and their parameters are used in this research.



(a) (b)

Figure 1: (a) Conventional equivalent circuit model, **(b)** Transformer-type equivalent circuit model.

In this research k is taken as 0.98 and $\angle k = 0^{\circ}$ for the aggregate motor. Figure 1(a) shows the equation below is derived

$$Z_S{}^{agg} = \frac{1}{\sum_{i=1}^{N} \frac{1}{Z_S{}^{i}}} \; where, Z_S = Z_2 + Z_3, \tag{1}$$

Other derivations can be found from equation (3.3) until equation (3.9) as proposed by Pillay *et al.*, (1998) respectively.

2.1.1 Induction motor aggregation based on no-load test and locked-rotor test (method 2)

This method is proposed by Karakas *et al.*, (2009) where the parameters of the aggregate induction motor are determined from two operating conditions, i.e., no-load and locked-rotor conditions. However, the above method was first proposed by Uchida *et al.*, (2000) and in this research, the equivalent circuit parameters of the aggregation model are determined based on the same procedure. Figure 2 was used for identification of model parameters of the aggregated IM. In the no-load operating conditions it is assumed that slips of all the induction motors are equal to zero while in the locked-rotor conditions, the slips of all induction motors are equal to unity. The equations used to obtain the aggregate model were introduced by Karakas *et al.*, (2009) and can be found from (1)-(21) respectively. Figure 2 shows the equivalent circuits of the aggregate induction motor load, where R_S-stator resistance, X_S-stator reactance, Rr-rotor resistance, Xr-rotor reactance, Xm-magnetizing reactance and S-Slip of the induction motor respectively whose parameters of the aggregated motor model are identified.

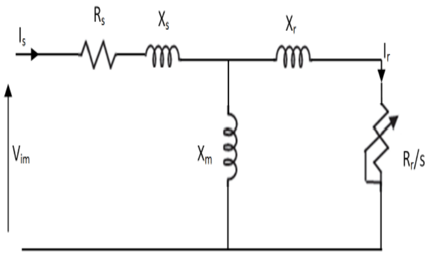


Figure 2: Classical equivalent circuit model of an induction motor

Generally, grouping criteria is used to identify and group homogeneous motors. The inertia and open circuit time constant are often used to classify motors. Uchida *et al.*, (2000) has developed a grouping criterion that may be expressed as:

G = a x b x H (2)

a = Xm/R2 (3)

b = (X1 + X2)/R1 + R2 (4)

The group is homogeneous if $1 \leq \dfrac{Gmax}{G\min} \leq 2.5$ (5)

Using the above grouping criterion, the different sizes of motors are classified into different groups. Aggregation based on this method is then done for different motor groups separately to find aggregate motors from each group. Table 1 shows typical parameters for large-scale IM.

Table 1: Typical Parameters for individual large induction motors

HP	RS	Rr	XS	Xr	Xm	H
1000	0.0158	0.0104	0.0851	0.0851	7.63	0.711
500	0.0185	0.0132	0.0851	0.0851	3.81	0.527
250	0.0241	0.0141	0.0864	0.0864	3.03	0.659
500	0.0185	0.0132	0.0851	0.0851	3.81	0.527

3.0 TEST SYSTEM DESCRIPTION

A Charles Gross 16 bus test system model in Figure B.1 (in appendix) was used in the analysis of the effectiveness of IM using the two methods of aggregation. It consists of nine lines, three generators, and seven load points. The three generators are a steam plant located at Rogers, a hydrogenation plant at Russel Dam and a tie line to an external system connected at Lowry substation. The cities Grigsby, Feasterville, Philipsburg and Honnell represent the major load centers. The hydrogenation plant at Russel Dam and the steam plant at Rogers also take significant loads from the system. The parameters of the system used by Muriithi *et al.*, (2011) were used for analysis. Bus 3 of the 16 bus was selected for analysis of the system as detailed below:

Total bus load = 10 Mw
Static load = 8.32 Mw
Dynamic load = (10-8.32) = 1.68 Mw
1.68 Mw = (1.68*^6/746) = 2250 Hp

Four individual and aggregate motors whose total load was 2250 Hp were analyzed and various parameters of the induction motor identified both under steady-state operation and under transient fault. The fault was set to occur at 0.25 seconds and cleared at 0.3 seconds. The purpose for creating the fault was to compare the suitability of aggregation methods in identification of the motor parameters and compare with steady-state operation for voltage stability analysis.

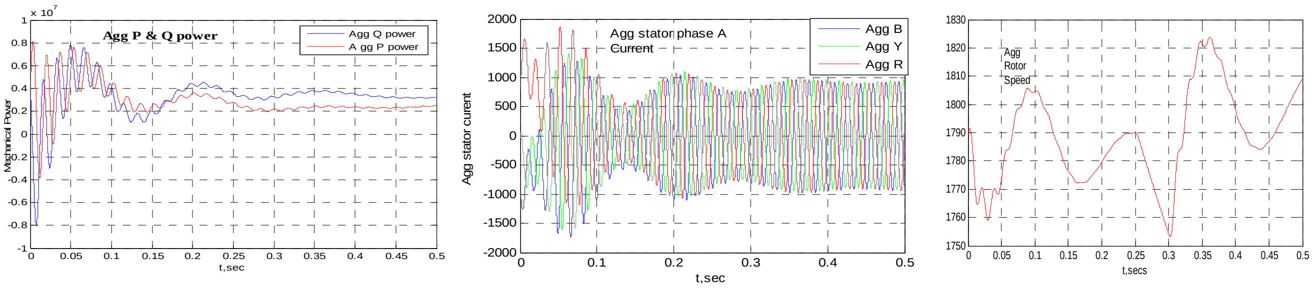
3.0 RESULTS AND DISCUSSION

In this research, an IEEE-16 bus standard network was used to show suitability and accuracy of aggregation methods in identification of motor parameters for analysis of voltage stability. Four IM of total load 2250HP were connected in parallel on bus 3. The Table 2 compares the suitability the two methods of aggregation against the standard motor parameters. From the result, it shows that method 2 is more accurate in the identification of the aggregate motor parameters than method 1 and therefore better suited for voltage stability analysis of any complex power system. It should be noted that when the rotor is not turning the slip is 100 % and at no-load, any increase in mechanical load will result in slip increase.

Table 2: Comparison of Aggregated IM parameters

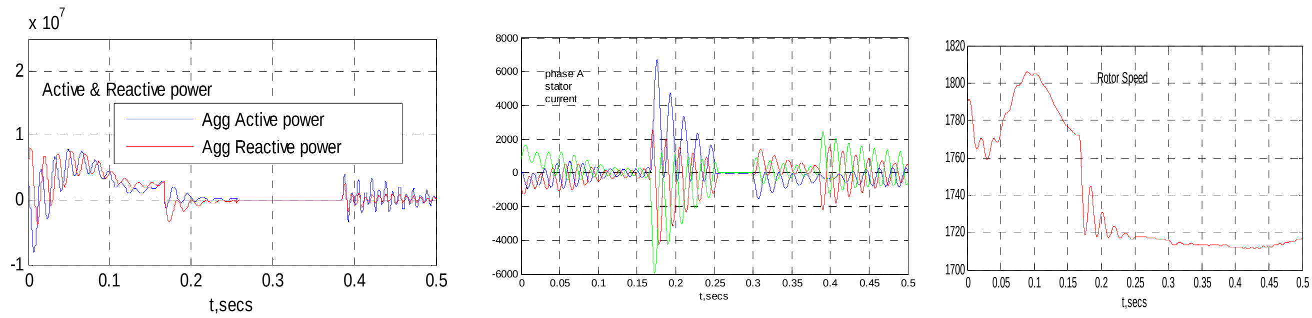
parameters	P_{agg}	R_{1agg}	$R_{2}agg$	X_{1agg}	X_{2agg}	X_{Magg}	V p.u
Aggregation method 1	2250	0.02	1.85	0.035	0.035	1.715	1
Aggregation method 2	2250	0.022	0.047	0.050	0.050	1.95	1
Typical data	2250	0.022	0.047	0.050	0.050	1.95	1

Figures 3 and 4 demonstrate the effect of steady-state and transient operation on aggregated induction motors. The aggregate model closely resembles that of the four individual motors. Figures 5 and 6 show the result of the Steady state and transient operation of the individual induction motors. The graphs clearly draw a close similarity of the result obtained from the aggregation model to that obtained from the individual motors.



(a) (b) (c)

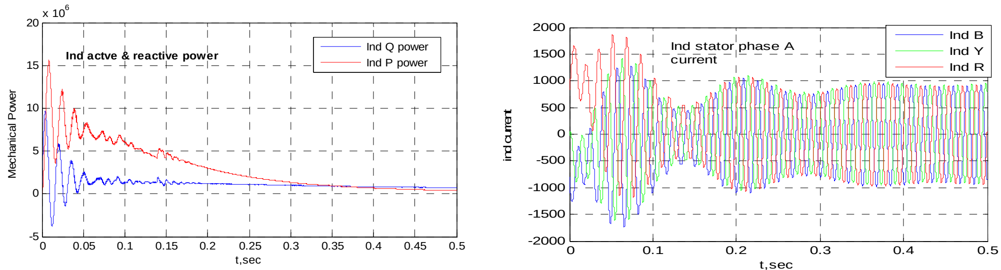
Figure 3: Steady-state operation of the four aggregate IM **(a)** aggregate active and reactive power response, **(b)** aggregation of stator phase A current, **(c)** aggregate rotor speed.



(a) (b) (c)

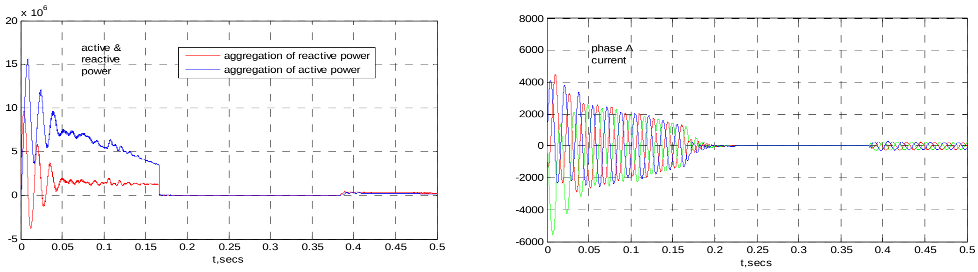
Figure 4: Switching transient responses of the 4 aggregate IM **(a)** aggregate active and reactive power response, **(b)** aggregation of stator phase A current, **(c)** aggregate rotor speed.

Figures 7(a) and Figure 7(b) show the suitability of of the two aggregation methods using MB-PSS on the aggregated IM under a system disturbance. The result shows that the MB-PSS provides a better damping of the oscillatory modes with method 2 compared to method 1. Therefore, Method 2 can be extensively used in accurate identification of the aggregate motor parameters in any complex power system under fault condition. The method is therefore best suited for volatge stability analysis.



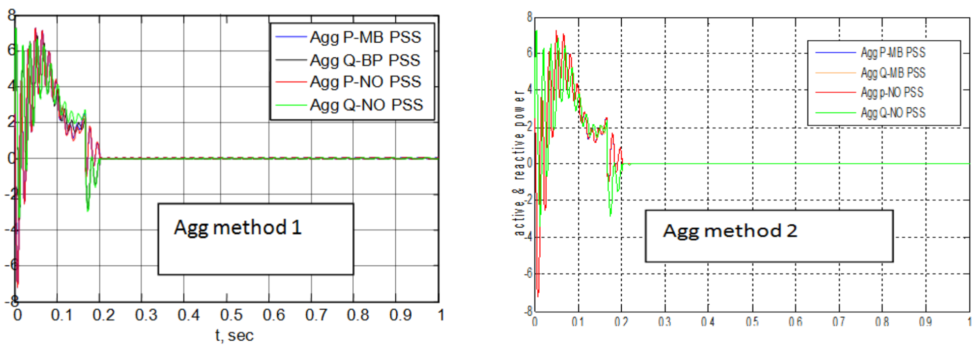
(a) (b)

Figure 5: Steady state operation of the individual IM, **(a)** Summation of the active & reactive power responses, **(b)** Summation of the stator phase A current.



(a) (b)

Figure 6: Switching transient responses of four individual IM, **(a)** summation of active and reactive power responses, **(b)** Summation of the stator phase A current.



(a) (b)

Figure 7: **(a)** Aggregated active and reactive power Using MB-PSS for method 1, **(b)** Aggregated active and reactive power using MB PSS for method 2.

4.0 CONCLUSION

The results show that aggregation method 2 is accurate in identification of the aggregate motor parameters compared to method 1. Further, the introduction of MB-PSS to the aggregate motor model indicates that, method 2 is still superior in the analysis of voltage stability under dynamic condition of the power system. The aggregate IM parameters were compared to individual motor parameters and method 2 was found suitable. This validated the former method of aggregation employed. The objective of this research has been achieved. It has also been realized that unless a suitable method of aggregation is selected, the results is bound to generate some errors. This does not resonate well with system control operators and power system engineers whose responsibilities is to ensure that the power system is run with minimal disturbances. It has also been proved that method 2 has good potential to be used in modelling of large motors in any complex power system because of its high accuracy. However, there is need to re-asses method 1 to identify why the aggregate motor parameters are not as accurate as method 2. The paper also proposes use of hybrid methods of motor aggregation for enhanced accuracy of the motor parameters. Therefore, for better analyses of power system voltage stability, aggregation of IM is crucial for accurate motor parameters identification and their sensitivity to various power system dynamic conditions.

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APPENDICES

Table A.1: Typical Induction Motors Parameters

R_S	Rr	X_S	Xr	Xm	H	RPM
0.02	0.04	0.03	0.03	1.21	0.71	1469
0.02	0.05	0.05	0.05	1.95	0.78	1435
0.02	0.04	0.05	0.05	2.31	0.79	1465
0.01	0.05	0.05	0.05	2.51	1.06	1485

Table A.2: Typical Parameters for Individual Small Induction Motors

HP	RS	Rr	XS	Xr	Xm	H	RPM
3	0.02	0.037	0.035	0.035	1.21	0.707	1760
25	0.022	0.047	0.05	0.05	1.95	0.528	1695
50	0.015	0.040	0.053	0.053	2.31	0.79	1750
100	0.011	0.047	0.053	0.053	2.51	1.06	1705

Table A.3: System load dataTable

BUS	P(MW)	Q(MVAR)
1	-	-
2	0	0
3	10	55
4	0	0
5	75	15
6	0	0
7	90	20
8	0	0
9	15	4
10	0	0
11	0	0
12	0	0
13	50	2
14	35	3
15	0	0
16	150	20

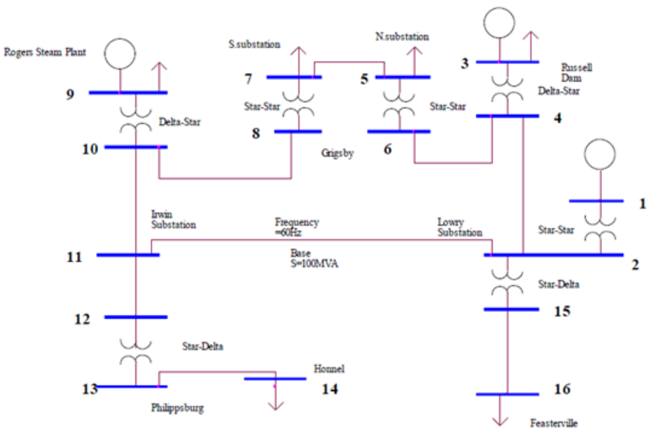

Figure B.1: Single line diagram of the 16-bus test model.

Transmission Line Parameters for 16 bus test system
R1= 0.01273 Ohms/km, R0=0.3864 Ohms/km
L1=0.9337 mH/km, L0=4.1264 mH/km
C1=12.74 nF/km, C0=7.751 nF/km
Line length: 156km

Base Voltage Specifications
345kV Bus 1
230kV Bus 2, 4, 6, 8, 10, 11 and 12
115kV Bus 5, 7, 15, 16
69kV Bus 13, 14
13.8kV Bus 3,