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On Aggregation Requirements for Harmonic Stability Analysis in Wind Power Plants

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***Abstract*— In harmonic stability studies, stable operation of a power system must be ensured at any possible configuration. This leads to a large number of cases due to the high number of components in a power system. An aggregated model can be used to lower the complexity and to reduce the number of different cases. In other words, several similar converters (e.g. Wind Turbine Generators) can be replaced by a converter with larger ratings. In most cases, aggregated models work well for stability studies, however, in some cases the aggregation might result in a wrong evaluation of stability. The aggregation reduces the complexity of the system by removing some state-variables of the overall system matrices; however, sometimes these removed variables contain some important information about the stability of the system. In this paper this problem is shown by a case study and it is evaluated by different methods, and a solution is also proposed.**

Keywords-Aggregation; Harmonic stability; Model Order Reduction; Voltage Source Converter; Wind Power.

I. INTRODUCTION

Power electronic converters offer more efficiency and more controllability to modern wind power plants [1]–[3] but at the cost of additional harmonics. The harmonics may trigger the parallel and series resonances in the power system [4]. The power converters may also interact with each other or other passive elements such as cables and transformers, and this might lead to instability [5], [6]. Therefore, the stable and proper operation of the windfarm must be verified at different situations in the design phase by using the harmonic analysis methods.

The Wind Turbine Generators installed in Wind Power Plants are generally voltage source converters, which are connected in parallel through some passive harmonic filters and array cables. In [7] and [8] it has been shown that the stability analysis of multi-paralleled converters is a bit different from single converter systems, and in some cases internal resonances might happen. This is very similar to a case where a group of WTs are considered as one converter to speed up the simulation and simplify the stability analysis. However, [7] and [8] have considered a case where all converters are solidly connected to the Point of Common Coupling (PCC) and have not considered the effects of the connecting power cables/lines.

In a large power system, which consists of many active and passive elements, the resulting transfer functions/matrices are of high order due to a high number of elements. To overcome this, an aggregated model can be used to combine some elements into a new element with the same dynamical order but with adjusted parameters [3]. For instance, Fig. 1 (a) shows two similar converters, which are connected to the PCC using similar cables. The new aggregated model can simply be replaced by changing the parameters as follows:

$$Z_l = Z_{l1} \parallel Z_{l2} = Z_{l1}/2 \qquad (1)$$
$$Y_c = Y_{c1} + Y_{c2} = 2Y_{c1} \qquad (2)$$

where, Y_c is the equivalent admittance of the converter, which includes all passive and active components, and Z_l is the cable impedance.

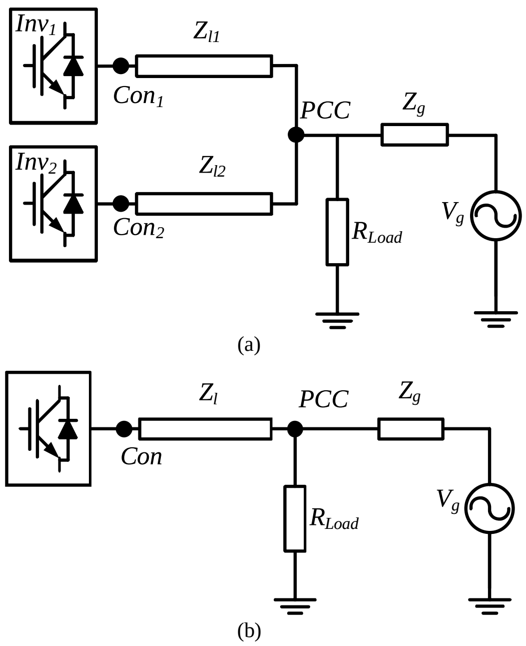

Fig. 1. The considered power system: (a) full detailed representation (b) simplified (aggregated) representation.

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In this paper the use of aggregated models for stability studies is investigated and some problems are reported in using them. The problem is studied thoroughly using different stability evaluation methods and the origin of the problem is identified and a method is proposed to avoid a wrong evaluation of the stability of the system.

II. Problems when Aggregation is Used

Equation (3) shows the relationship between the node voltages in an electrical circuit with the currents injected to the nodes (see Fig. 2).

$$\begin{bmatrix} I_1(s) \\ \vdots \\ I_m(s) \\ \vdots \\ I_n(s) \end{bmatrix} = \begin{bmatrix} Y_{11}(s) & \cdots & Y_{1m}(s) & \cdots & Y_{1n}(s) \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ Y_{m1}(s) & \cdots & Y_{mm}(s) & \cdots & Y_{mn}(s) \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ Y_{n1}(s) & \cdots & Y_{nm}(s) & \cdots & Y_{nn}(s) \end{bmatrix} \begin{bmatrix} V_1(s) \\ \vdots \\ V_m(s) \\ \vdots \\ V_n(s) \end{bmatrix} \tag{3}$$

In this power system, the current set points are inputs and the node voltages are outputs of the control system, which can be interpreted as a Multi-Input Multi-Output (MIMO) system. Equation (4), which is actually the impedance matrix of the system, defines the transfer matrix of the system.

$$[V(s)] = [Z(s)][I(s)] \tag{4}$$

The impedance matrix (Z_{Bus}) of the system shown in Fig. 1 (a) can be calculated by simply inverting the admittance matrix (Y_{Bus}) that is:

$$Y_{bus} = \begin{matrix} Nodes \\ Con_1 \\ Con_2 \\ PCC \end{matrix} \begin{matrix} \begin{matrix} Con_1 & Con_2 & PCC \end{matrix} \\ \begin{bmatrix} Y_{c1} + Y_{l1} & 0 & -Y_{l1} \\ 0 & Y_{c2} + Y_{l2} & -Y_{l2} \\ -Y_{l1} & -Y_{l2} & Y_{l1} + Y_{l2} + Y_g \end{bmatrix} \end{matrix} \tag{5}$$

where, Y_{ci} is the equivalent admittance of the ith converter including all passive elements and controllers, Y_{li} is the equivalent line/cable admittance, and Y_g is the grid admittance plus the load admittance. It can be seen from (6) that all elements have the same characteristic equation, i.e. the same poles.

If the system is symmetrical, i.e. identical converters and identical cables, then the elements of the new impedance matrix as written in (7) do not have the same poles (see the highlighted elements) due to some pole/zero cancelations. The transfer matrix of the aggregated system can also be expressed as:

$$Z_{bus} = \frac{1}{\Delta_{aggr}} \begin{bmatrix} Y_g + 2Y_l & Y_l \\ Y_l & Y_c + Y_l \end{bmatrix} \tag{8}$$

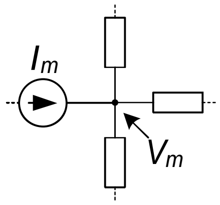

Fig. 2. Voltages of the nodes and currents injected to them.

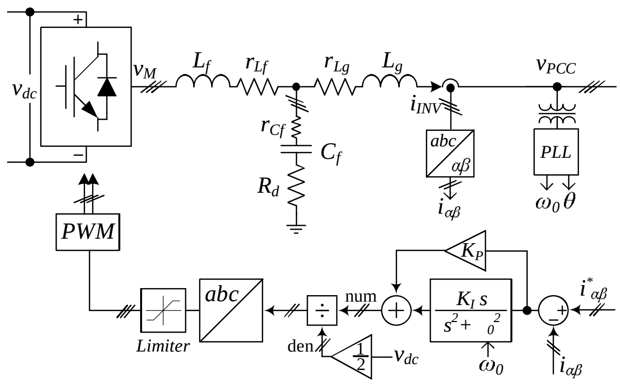

Fig. 3. Internal control structure of the converter.

TABLE I. The Parameters of the Considered Power System

Symbol	Description	Value
f_{sw}	Sampling frequency [kHz]	10
V_{dc}	DC-link voltage [V]	750
L_f	Inverter side inductor of the filter [mH]	0.87
C_f	Filter capacitor [µF]	22
L_g	Grid side inductor of the filter [mH]	0.22
r_{Lf}	Parasitic resistance of L_f [mΩ]	11.4
r_{Cf}	Parasitic resistance of C_f [mΩ]	7.5
r_{Lg}	Parasitic resistance of L_g [mΩ]	2.9
R_d	Damping resistance [Ω]	0.2
K_P	Proportional gain of the controller	5.6
K_I	Integrator gain of the controller	1000
V_g	Grid voltage (phase-ground) rms	220
R_g	Grid equivalent resistance [Ω]	0.1
L_s	Grid equivalent inductance [mH]	3
L_1	Inductance of Cable 1[mH]	0.3
L_2	Inductance of Cable 2[mH]	0.3
R_{Load}	Load resistance [Ω]	40

$$\Delta_{aggr} = Y_c Y_g + 2Y_c Y_l + Y_g Y_l$$

It is clear from (8) that if one uses the aggregated model for stability evaluation some dynamics of the system cannot be observed, and if the hidden pole is unstable, then the stability evaluation is wrong. It must be noted that the same conclusion can be made by the Impedance-Based Stability Analysis (IBSA) since it uses the impedance seen from the aggregated WT terminal, which is $Z_{1,1}$ of (8) [6].

$$Z_{bus} = \frac{1}{\Delta_{full}} \begin{bmatrix} (Y_{c2} + Y_{l2})(Y_{l1} + Y_g) + Y_{c2}Y_{l2} & Y_{l1}Y_{l2} & Y_{l1}(Y_{c2} + Y_{l2}) \\ Y_{l1}Y_{l2} & (Y_{c1} + Y_{l1})(Y_{l2} + Y_g) + Y_{c1}Y_{l1} & Y_{l2}(Y_{c1} + Y_{l1}) \\ Y_{l1}(Y_{c2} + Y_{l2}) & Y_{l2}(Y_{c1} + Y_{l1}) & (Y_{c1} + Y_{l1})(Y_{c2} + Y_{l2}) \end{bmatrix} \tag{6}$$

$$\Delta_{full} = Y_{c1}Y_{c2}Y_g + Y_{c1}Y_{c2}Y_{l1} + Y_{c1}Y_{c2}Y_{l2} + Y_{c1}Y_gY_{l2} + Y_{c2}Y_gY_{l1} + Y_{c1}Y_{l1}Y_{l2} + Y_{c2}Y_{l1}Y_{l2} + Y_gY_{l1}Y_{l2}$$

$$Z_{bus} = \frac{1}{\Delta_{sym}} \begin{bmatrix} \frac{(Y_c + Y_l)(Y_l + Y_g) + Y_cY_l}{(Y_c + Y_l)} & \frac{Y_l^2}{(Y_c + Y_l)} & Y_l \\ \frac{Y_l^2}{(Y_c + Y_l)} & \frac{(Y_c + Y_l)(Y_l + Y_g) + Y_cY_l}{(Y_c + Y_l)} & Y_l \\ Y_l & Y_l & (Y_c + Y_l) \end{bmatrix} \tag{7}$$

$$\Delta_{sym} = Y_cY_g + 2Y_cY_l + Y_gY_l$$

To verify the reported problem of aggregation, a case study of the system shown in Fig. 1 with the parameters listed in Table I is presented. A proportional resonant controller as shown in Fig. 3 is used to control the output current. The admittance of the shown converter [6] is

$$Y_o = \frac{Z_{Lf} + Z_{Cf}}{Z_{Cf}Z_{Lf} + Z_{Cf}Z_{Lg} + Z_{Lf}Z_{Lg} + G_c G_{PWM} Z_{Cf}} \quad (9)$$

where, G_c is the current controller transfer function, and G_{PWM} models the PWM delay. The two converters can be aggregated into one converter with the parameters as

$$\acute{Z}_{L_f} = Z_{L_f}/2, \qquad \acute{Z}_{L_g} = Z_{L_g}/2$$
$$\acute{Z}_{C_f} = Z_{C_f}/2, \qquad \acute{G}_c = G_c/2 \quad (10)$$
$$\acute{G}_{PWM} = G_{PWM}$$

Fig. 4 shows the pole plot of the considered case study for both full and aggregated models. It can be seen that there are two unstable poles in the full system that are not observable in the aggregated model. The impedance based stability analysis also gives the same conclusion. It must be noted that the Nyquist diagrams as shown in Fig. 5 do not encircle the critical point (the blue curve encircles twice; however in two different directions, therefore, the total number of encirclements is zero). However, there are some Right Half Plane (RHP) poles in the open loop transfer function of the full system, therefore, the Nyquist stability criterion states that the system should be unstable.

The system is predicted to be stable when an aggregated model is used. Therefore, it is interesting to see these results by means of time domain simulations that are done in PLECS software. Fig. 6 shows that when the aggregated model is used the system works stable, while the full model is unstable.

To prove that the origin of this instability is inside the aggregated model, a participation factor analysis is performed [9]. Table II shows the two most poorly damped poles of the system and the contributors to them. It can be seen that the state variable of the external network (current of the grid inductance in here) has no impact on the unstable pole pair. Furthermore, the mode shapes (corresponding right eigenvector) of the unstable poles reveal that this instability is because of the internal oscillation between the two converters [9]. The mode shapes as listed in Table III show that the two converters are oscillating against each other (180° phase shift) for the unstable pole but they behave similarly to the stable pole. Thus, it can be concluded that since the inverters have a similar behavior to the second pole the aggregation can be used for studying that pole. However, the aggregation cannot be used for the unstable pole. This conclusion can also be done from Fig. 4.

III. PROPOSED METHOD

To avoid this wrong evaluation in using aggregated models, a step-by-step method is suggested. It has been shown in (7) and (8) that the polynomial (Y_c+Y_l) is the main difference between the full and aggregated models, and if this polynomial has some unstable roots, then the system is internally unstable. This polynomial is not dependent on the

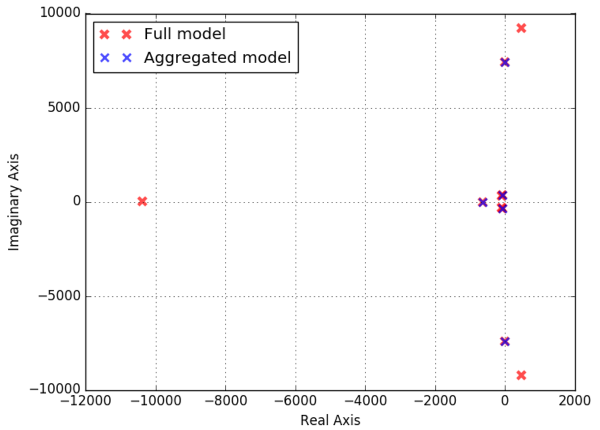

Fig. 4. Poles of the considered case study.

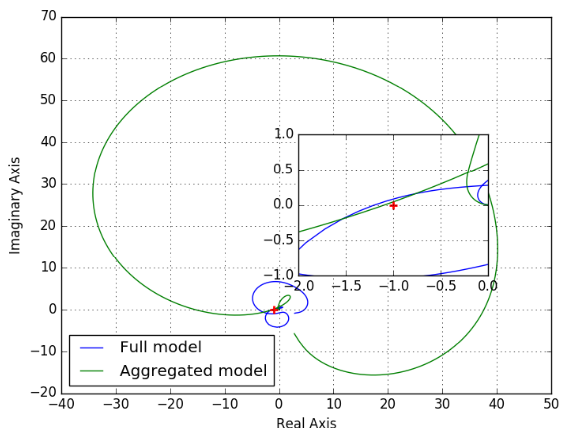

Fig. 5. Nyquist diagrams of the IBSA for the considered case study.

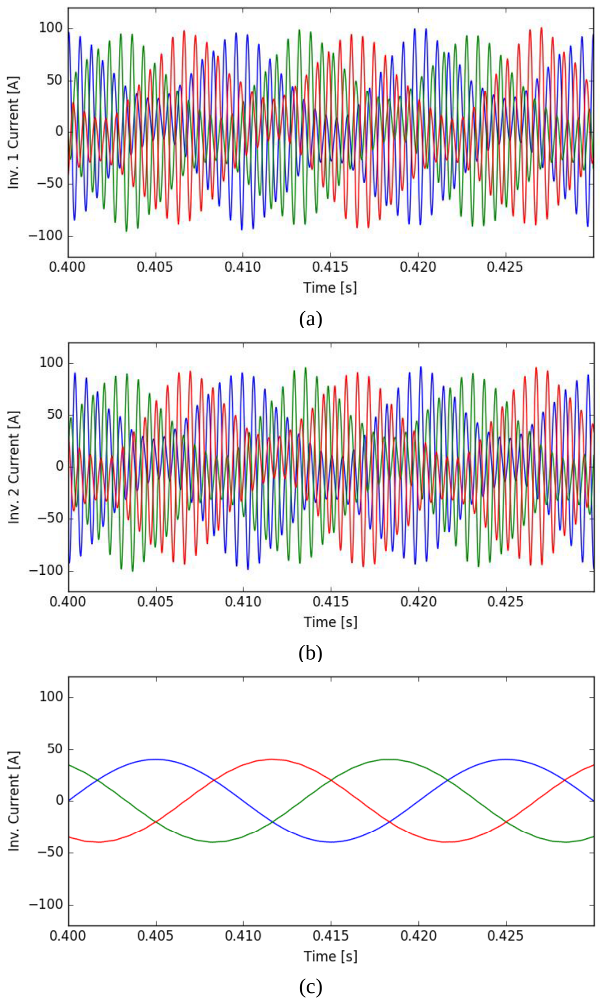

Fig. 6. Output currents of (a) Inverter 1 in full model (b) Inverter 2 in

TABLE II. CONTRIBUTORS TO THE MOST CRITICAL POLES

Contributors \ Poles		470.9±9225j	-11±7421j
Full model	Inverter 1	46%	49%
	Inverter 2	46%	49%
	Grid	0	1.5%
	Cable 1	4%	0.05%
	Cable 2	4%	0.05%
Aggregated model	Inverter		0.98
	Grid		0.015
	Cable		0.001

TABLE III. MODE SHAPES OF THE CONVERTERS

State variables \ Poles	470.9+9225j	-11-7421j
Inverter 1.s2	0.76∠-1.5°	0.19∠-21.6°
Inverter 2.s2	0.76∠178.5°	0.19∠-21.6°
Inverter 1.s4	0.37∠18.8°	0.38∠165.2°
Inverter 2.s4	0.37∠-161.2°	0.38∠165.2°
Inverter 1.s5	0.16∠52.0°	0.76∠169.4°
Inverter 2.s5	0.16∠-128.0°	0.76∠169.4°
Inverter 1.s3	0.08∠-119.6°	1.05∠7.3°
Inverter 2.s3	0.08∠60.4°	1.05∠7.3°

external network, therefore, if the subsystem is stable (or has enough damping) alone, the aggregation can be used safely. The closed-loop transfer matrix of the first step as shown in Fig. 7 is

$$Z_{bus} = \frac{1}{Y_c + Y_l}\begin{bmatrix}1 & 0\\0 & 1\end{bmatrix} \quad (11)$$

Therefore, if the stability is ensured inside any aggregated model, the possible pole/zero cancellation cannot create any instability. Fig. 8 shows that there is an unstable pole pair in the aggregated system and if aggregation is used, these poles might be concealed. These poles are exactly moved to the full

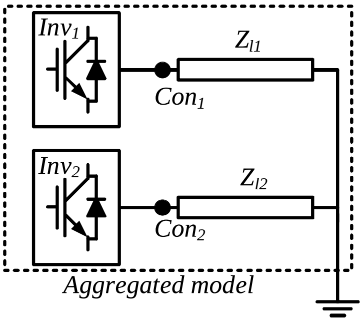

Fig. 7. Investigating the stability of the aggregation of the systems alone.

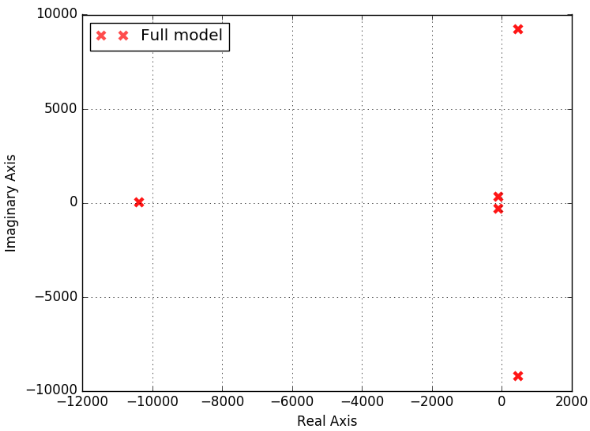

Fig. 8. Internal poles of the aggregated system as shown in Fig. 6.

model (see Fig. 4) because they do not depend on the external network.

IV. CONCLUSION

When an aggregated model is used, the focus is only on the external behavior of the subsystem, and the internal dynamics of the system might be concealed. If the subsystem is internally unstable then the instability cannot be predicted by the stability assessment methods for the aggregated system, and this increases the chance of harmonic pollution and instability in the system. In this paper, this problem is reported for a multi-converter system and a solution is proposed to foresee the problem. The Impedance Based Stability Criterion and Eigenvalue-Based Stability Analysis methods are used for the stability evaluation, and the possible instability is identified by means of eigenvector analysis. A step by step method is proposed to first analyze each aggregated model from a stability perspective. Then, if the subsystem is stable enough, the aggregation can be used safely for system studies.

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