PMSG Synchronization Control Algorithm based on the Active Damping Principle

Marko Vekić, Stevan Grabić, Evgenije Adžić, Zoran Ivanović, Vlado Porobić
Faculty of technical sciences
Novi Sad, Serbia
vekmar@uns.ac.rs

***Abstract*— In this paper the modified active damping law was used to damp oscillations during the synchronization process of PMSG cascade. Due to the imposed capacity limit of the converter and exclusive reactive power injection, the damping ability is limited. Boundaries of the area which defines possible synchronization depend on PMSG initial speed and the difference between the grid and PMSG angle at the moment of connection. Exhaustive tests by means of the state of the art HIL emulation were performed to prove both the modified damping law and its area of application.**

Keywords-PMSG (Permanent Magnet Synchronous Generator), PMSG cascade, active damping, modified active damping, area of operation, boundaries,

I. INTRODUCTION

Active Damping Principle is proposed as the part of control algorithm strategy in various grid connected applications. The aim of active damping is very similar or the same as the purpose of passive damping structures (based on passive elements) – to damp oscillations during the transition period and improve stability. In contrast to passive dampers, active damping topology contain power electronics converters as active elements. It should be noted that active damping is much different from one similar structure - active filter. The purpose of active filtering is to suppress or eliminate undesired harmonics in the system, while the active damping primarily damps transient oscillations. Modus operandi of the active damping is to use the converter (say 3-phase inverter) and control it in such manner to emulate the "programmable" impedance, effectively increasing the system original damping level. The concept is tested in many applications. The active damping principle is employed in FACTS to improve the transient stability of the system in case of power flow fluctuations [1]–[6], and grid voltage disturbances [7]–[9]. Recently a number of papers propose the active damping to improve the stability of LLCL-filter based grid connected inverters [10] – [12].

In [13] the concept of permanent magnet synchronous generator (PMSG) cascade is proposed (Fig. 1) to actively damp the system subjected to the input power fluctuations (changes in the input load torque). This is essentially achieved through the series converter connected in the open winding of the PMSG which effectively modulates the overall reactance. In this paper the similar approach with modified algorithm is employed to help the PMSG direct connection to the grid. The results are verified using state – of – the art Hardware In the Loop (HIL) platform [14].

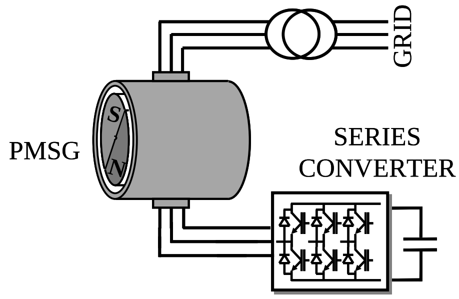

Figure 1. PMSG Cascade

II. ACTIVE DAMPING ALGORITHM FOR PMSM CASCADE

The main components of a PMSG cascade system (see Fig. 1) are: a grid-connected PMSG and a small series converter (20% of rated power) in the star point of the open winding PMSG) [13].

In Fig. 2, the synchronous generator is modeled as a three phase voltage source u_{EMF} in series with synchronous inductance x_S, while the grid and the series converter are modeled as two additional three-phase voltage sources, u_{GRID} and u_{SC}, respectively.

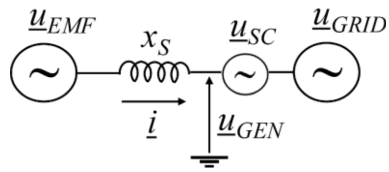

Figure 2. Simplified model of PMSG Cascade

Power flow through the system is controlled by injecting reactive voltage u^r_{SC} whose phase is shifted 90◦ with respect to the line current vector. The additional requirement is that injected reactive voltage component u^r_{SC} should not exceed 0.2 [p.u.].

The grid is assumed to be ideal (the infinite power) where U_{GRID} = 1 [p.u.], while the PMSG rotor speed varies only slightly around its nominal value, i.e. n = 1 [p.u.]. It also implies U_{EMF}=1. So simplified system can be described with following equations:

$$m_{el} = \frac{\sin\theta}{x_S}\left(1 - \frac{u_{SC}^r}{\sqrt{2\cdot(1-\cos\theta)}}\right) \quad (1)$$

$$\tau_{mec}\frac{dn}{dt} = M_m - m_{el} \quad (2)$$

$$\frac{1}{\omega_{grid}}\frac{d\theta}{dt} = n - 1 \quad (3)$$

The first part of (1) is well known expression which describes (in [p.u.]) the PMSG with rounded rotor connected to the ideal grid. Generally this equation defines the power flow between two voltage sources connected through the reactance (x_s here). However, the second part of the equation depends on the injected voltage of series converter, u^r_{SC}. Controlling this voltage, the electrical torque m_{el} can be modulated and hence, this modulated torque could bring the damping ability. Using the electro-mechanical analogy, it can be shown [13] that the voltage u^r_{SC} should be generated as follows:

$$u_{SC}^r = -k_{dmp}\cdot\frac{d\theta}{dt}\cdot\operatorname{sgn}(\theta) \quad (4)$$

where k_{dmp} is the damping factor and θ is the angle difference between the grid voltage and induced PMSG electromotive force. After the start of synchronization this angle difference is usually called the power angle. The upper equation is actually the variation of well-known spring law applied to electromechanical phenomena [15]. From (1) and (4) it can be obtained:

$$u_{SC}^r = -k_{dmp}\cdot\frac{d\theta}{dt}\cdot\operatorname{sgn}(\theta) = -k_{dmp}\cdot\omega_{GRID}\cdot(n-1)\cdot\operatorname{sgn}(\theta) \quad (5)$$

which is basically the core of the control law for damping oscillations caused by the input (mechanical) torque changes.

III. SYNCHRONIZATION

A. Introduction

It is well known that for successful PMSG connection to the grid, appropriate grid voltage and emf vectors (magnitudes, angles and frequencies) should match. Even when voltage magnitudes ($U_{grid} = U_{gen}$) and frequencies ($n_{grid} = n_{gen}$) are the same, but not the phase angle ($\theta_{grid} \neq \theta_{gen}$), oscillations will occur as simulation results clearly confirm (Fig. 3). Of course these results are completely expected. Parameters of the simulated machine are given in [16]. The overall damping level of the system is even worse when we speak about the high power machine with relatively small stator resistance.

B. Modified active damping principle

The process of synchronization to the grid when voltage vectors are different essentially resembles the case when grid connected PMSG suffers load disturbances.

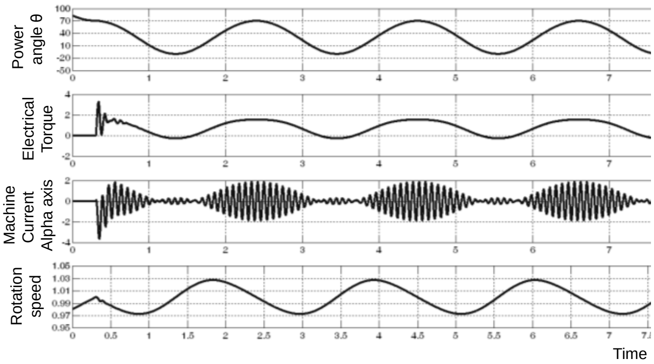

Figure 3. Synchronization attempt when the difference in phase angles is $\theta = 70°$ and $n_{grid} = n_{gen}$

The both processes include oscillations. Therefore, the idea to employ the active damping algorithm described in the section II. is actually very intuitive. However, the described control law (5) has to be modified, because in the case of the synchronization it cannot be assumed that PMSG speed is nominal, i.e. $n \neq 1$ [p.u.]. Therefore, PMSG speed appears in the further consideration as a variable which also implies variable $U_{EMF} = n\cdot\psi$, where ψ is permanent magnets flux. Following these modifications, the equation (1) becomes:

$$m_{el} = \frac{\psi}{n\cdot x_s}\cdot\sin\theta - \frac{\psi}{n\cdot x_s}\cdot\sin\theta\cdot\frac{U_{SC}^r}{\sqrt{1+n^2\cdot\psi^2-2\cdot n\cdot\psi\cdot\cos\theta}} \quad (6)$$

Accordingly, the control law accordingly is given by:

$$U_{SC}^r = -\frac{a}{2}\cdot n\cdot(n-1)\cdot\frac{\sqrt{1+n^2\cdot\psi^2-2\cdot n\cdot\psi\cdot\cos\theta}}{\sin\frac{\theta}{2}} \quad (7)$$

In the upper equation a is the damping coefficient instead of k_{dmp} from (5). The torque expression (6) now becomes:

$$m_{el} = \frac{\psi}{x_s}\cdot\frac{\sin(\theta)}{n} + a\cdot\frac{\psi}{x_s}\cdot(n-1)\cdot\cos\left(\frac{\theta}{2}\right) \quad (8)$$

In order to complete the control law, the coefficient a has to be determined. The control structure is given at the Fig. 4.

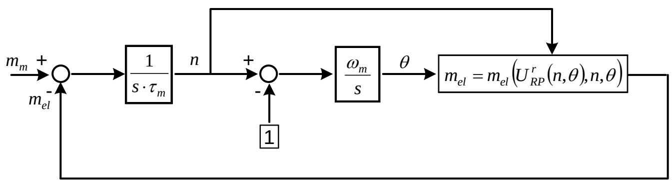

Figure 4. Synchronization control scheme

Although this control diagram looks pretty simple, the block which represent torque calculation is non-linear as (8) clearly shows. Therefore, in order to obtain coefficient a the linearization around the operation point has to be performed. It is justified to adopt the PMSG nominal value (n = 1 [p.u.]) for operation point because the process of synchronization should start when the speed approaches grid (nominal) speed. The linearized control diagram is presented on Fig. 5.

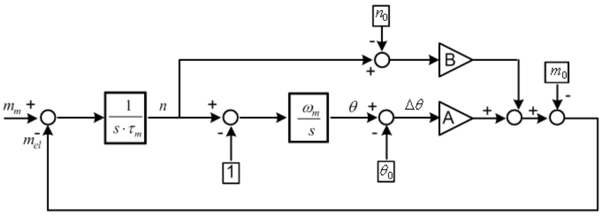

Figure 5. Linearized synchronization control scheme

The characteristic equation derived from Fig. 5 is the second order equation:

$$f(s) = s^2 + s \cdot \frac{B}{\tau_m} + \frac{A \cdot \omega_m}{\tau_m} \tag{9}$$

where: $A = \left.\frac{\partial m_{el}}{\partial \theta}\right|_{\theta_0, n_0}$, $B = \left.\frac{\partial m_{el}}{\partial n}\right|_{\theta_0, n_0}$ (10)

and m_{el} is defined by (8).

Observing (9), the coefficient ξ and natural frequency ω can be easily obtained from:

$$2 \cdot \xi \cdot \omega_n = \frac{B}{\tau_m} \text{ и } \omega_n^2 = \frac{A \cdot \omega_m}{\tau_m} \tag{11}$$

i.e: $\xi = \frac{B}{2 \cdot \sqrt{A \cdot \tau_m \cdot \omega_m}}$ (12)

Finally, from (10) and (12) desired damping coefficient a can be calculated as the function of ξ, and operation point θ_0, n_0 (the initial angle difference and PMSG speed value at the very moment of synchronization respectively). The operation point (θ_0, n_0) itself depends on the input mechanical torque M_m which accelerates PMSG. At the Fig. 6 dependency of the coefficient a as the function of the driving input torque in the full range of M_m from 0.1 to 1 [p.u.] is presented.

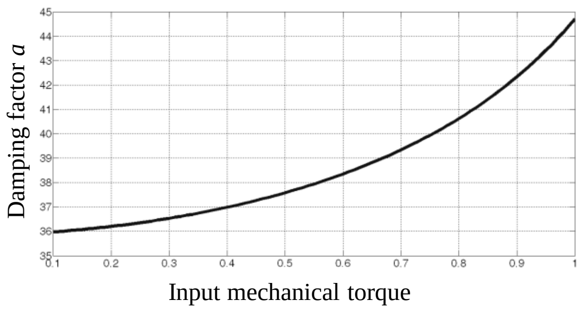

Figure 6. Damping factor *a*

From the upper diagram we can see that the coefficient a varies from 35.98 to 44.71 in the whole driving torque range. Therefore, we can adopt the average value, i.e. a = 38.7 in further calculations. Results presented later will justify such choice.

C. Synchronization feasibility

Let us apply the modified active damping law in the case from Fig. 3. The new situation is illustrated at the Fig. 7.

Obviously, the synchronization is accomplished successfully. Oscillations in the power angle, PMSG currents, speed and torque fade away completely after 2 s, while the transient process is properly damped.

However, keeping in mind that the capacity of the series converter is limited to 0.2 [p.u.], i.e:

$$\left| u_{sc}^r \right| \leq 0.2 \left[p.u. \right] \tag{13}$$

it is clear that the synchronization cannot be achieved in all instances, i.e. for all values of initial PMSG speed n_{init} and angle difference θ_{init}.

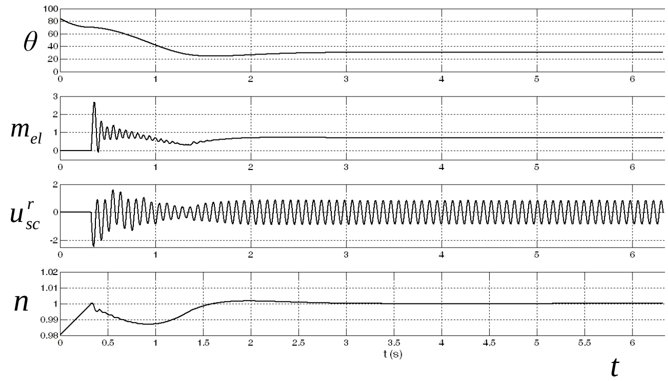

Figure 7. Synchronization attempt when the difference in phase angles is θ_{init} = 70°, $n_{grid} = n_{gen}$ and modified active damping law applied

Indeed, if the simulation is performed under the assumption that θ_{init} = - 150°, the situation is much different as shown at Fig. 8.

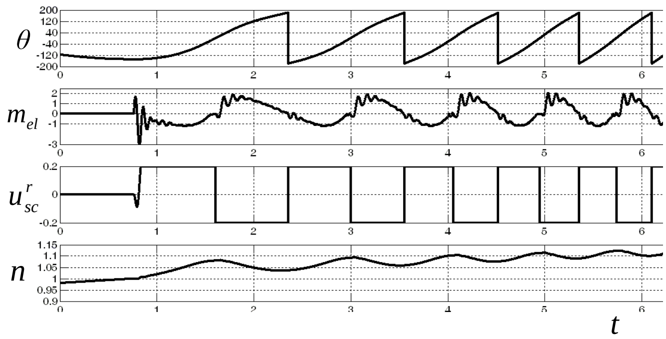

Figure 8. Synchronization attempt when the difference in phase angles is θ_{init} = 150°, $n_{grid} = n_{gen}$ and modified active damping law applied

Obviously, the synchronization was not successful. That means the application of the proposed modified active damping law has certain limits which are the consequence of (13).

D. Modified active damping law application area

Boundaries of the area where the modified active damping control principle is applicable have to be determined. For that purpose, a detailed mathematical and simulation model are developed [17] in order to find the range of the input mechanical torque M_m, initial angle difference θ_{init} and speed n_{init} for which the synchronization is possible. The simulation results are shown at the Fig. 9.

Results from the Fig. 9 are obtained under assumption that the initial PMSG speed at the moment of synchronization was n_{init} = 0.98 [p.u.], while the power angle (the difference between the grid and PMSG angle) and input mechanical torque are arbitrary values. It can be concluded that synchronization is possible for any value of the mechanical input torque in the range of [0.1,..,0.9, 1] when the initial power angle θ_{init} is in the range of -30º to 100º. These boundaries are essentially the consequence of the limited series converter voltage (13).

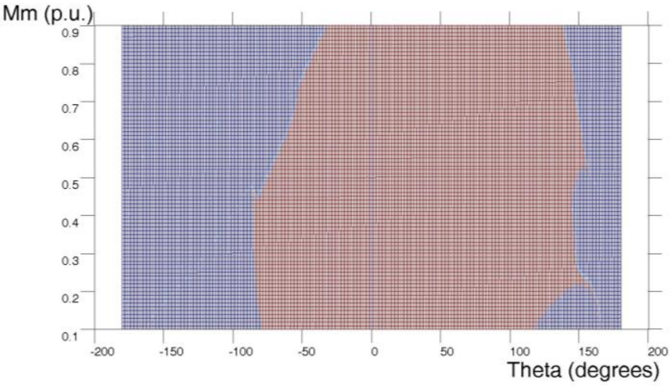

Figure 9. The area where synchronization is possible

After the area is obtained by means of the detailed simulation, we need to perform exhaustive testing in order to verify the proposed modified active damping law.

IV. EXPERIMENTAL RESULTS

In order to check the control law and its borders, we need to perform tests in all operation points, particularly on area border (Fig. 9) itself and a little beyond. Testing with the real hardware, even when using small power test bench would be dangerous and too laborious because we need to test the grid tied PMSG application. A very efficient alternative would be real time, hardware in the loop (HIL) emulation with extremely high simulation step, i.e. overall latency of 1 µs [14].

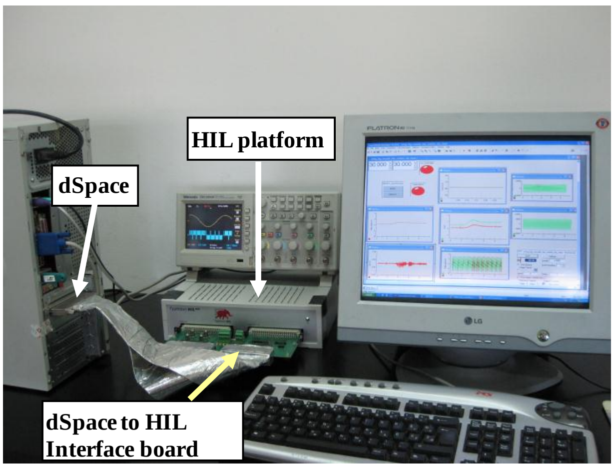

Figure 10. Experimental setup

Fig. 10 shows the experimental setup for evaluation of the proposed synchronization algorithm. *Dspace dS1104* is employed as the controller stage (Fig.5), while *Typhoon HIL400* platform is used to emulate the power stage (Fig. 1). Tests were performed for nine cases of input mechanical torque: M_m =(0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0) [p.u.]. For each case, three operation points were chosen regarding initial power angle θ_{init} – the upper boundary, the lower boundary and region between them. Here, only several characteristic results are shown.

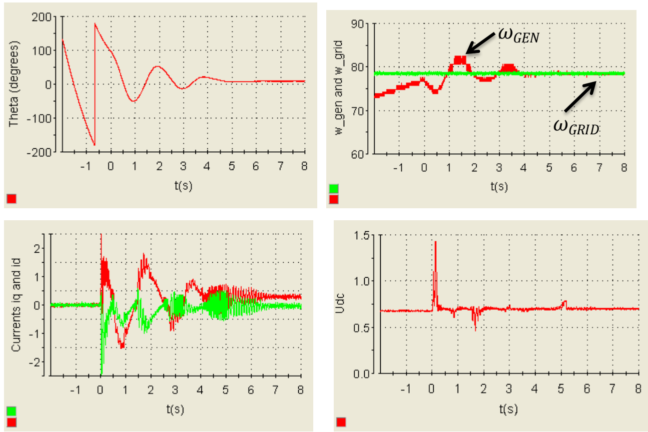

Figure 11. PMSG Synchronization when M_m=0.3 [p.u] and θ_{init}=115º

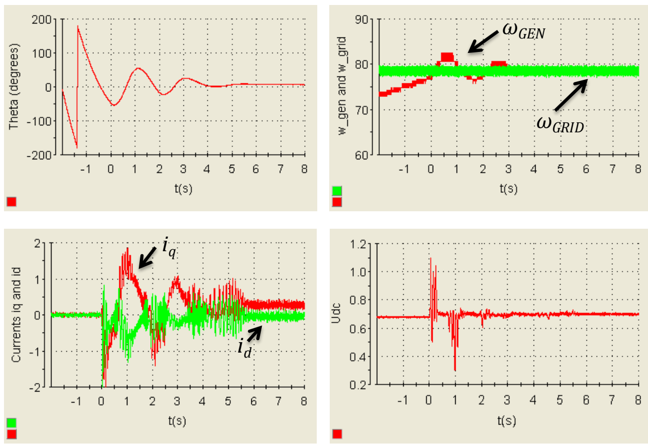

Figure 12. PMSG Synchronization when M_m=0.3 [p.u] and θ_{init}=-45º

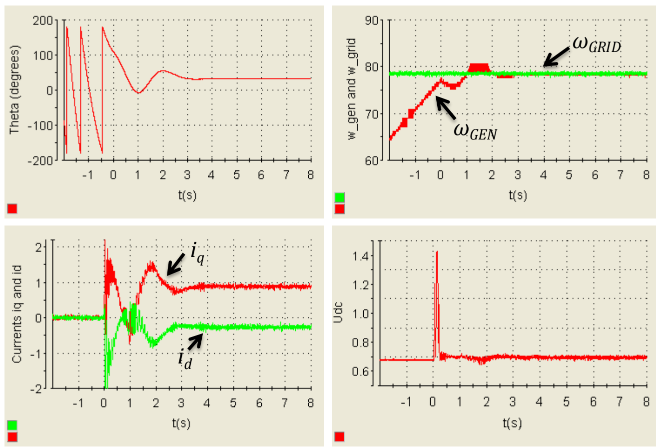

Figure 13. PMSG Synchronization when M_m=0.9 [p.u] and θ_{init}=120º

At displayed figures, ω_{GEN} represents an electrical speed of PMSG, ω_{GRID} is grid frequency, i_d and i_q are d and q components of the current in synchronous rotating frame where i_q is the current component proportional to the electrical torque.

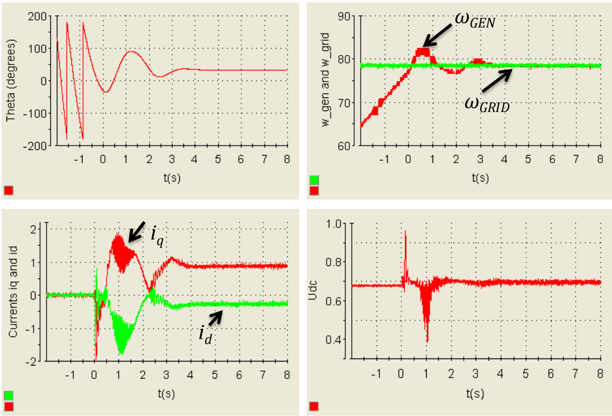

Fig. 14. PMSG Synchronization when M_m=0.9 [p.u] and θ_{init}=-35º

The upper results represent two characteristic cases: small input driving torque (M_m = 0.2 [p.u.]) and big driving torque (M_m = 0.9 [p.u.]) in two extreme cases; at the lower and upper border of the area (Fig. 9). From Fig. 11 – Fig.14 it can be concluded that synchronization is performed successfully.

At the Fig. 15 results are presented when the operation point is deeply into the safe area.

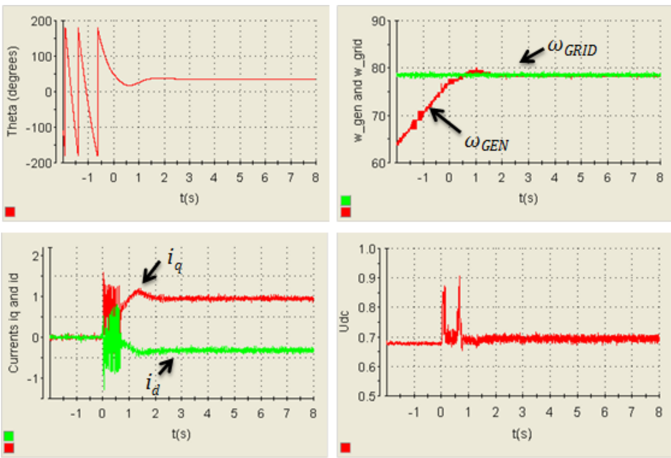

Figure 15. PMSG Synchronization when M_m=1.0 [p.u] and θ_{init}= 45º

According to expectation, the system response is very clear and smooth.

Further investigation was performed for cases when θ_{init} belongs to the area well beyond designated borders (Fig. 15).

From the figure bellow it is clear that the PMSG connection to the grid is not possible when the initial angle difference is significantly displaced from the pre-defined boundaries. However, the PMSG connection to the grid is still possible slightly beyond borders of the area defined by Fig. 9. In the purely theoretical scenario where no limits are imposed to the voltage injected by series converter, the synchronization would be possible for any instant in the range of θ_{init} = [-180°, …, 180°].

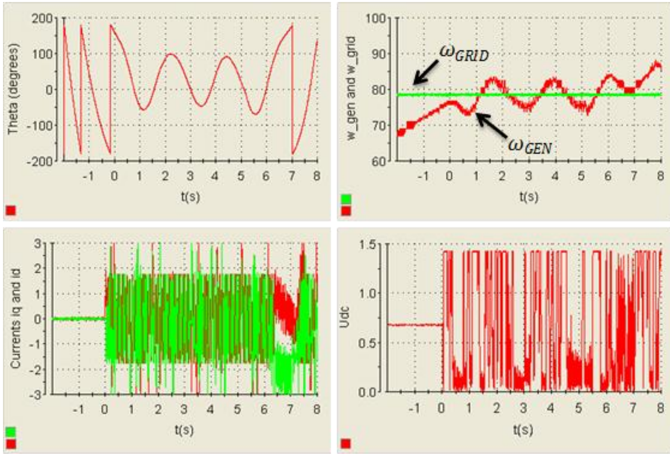

Figure 16. PMSG Synchronization when M_m=0.6 [p.u] and θ_{init}=160 º

V. Conclusions

The active damping principle is used successfully to cope with transient oscillations in grid-tied applications. In this paper the modified algorithm for PMSG cascade was employed to help PMSG direct connection to the electrical grid. It is assumed that converter injects only reactive voltage component equal to 0.2 [p.u.]. Therefore, the validity of algorithm is limited by initial synchronization conditions: angle difference, PMSG speed and driving input torque. The area of successful connection to the grid is determined using simulation and exhaustively tested by means of HIL emulation in all operation points of interest. The future research should deal with further modifications in the damping law principle.

Acknowledgment

This research was partially co-funded by the Ministry of Education, Science and Technological Development of Republic of Serbia under contract No. III 042004 and by the Provincial Secretariat for Science and Technological Development of AP Vojvodina under contract. No. 114-451-3508/2013-04.

References

[1] F. A. L. Jowder, “Influence of mode of operation of the SSSC on the small disturbance and transient stability of a radial power system,” *IEEE Trans. Power Syst*., vol. 20, no. 2, pp. 935–942, May 2005.

[2] B. T. Ooi, M. Kazerani, R. Marceau, Z. Wolanski, F. D. Galiana, D.McGillis, and G. Joos, “Mid-point sitting of facts devices in transmission lines,” IEEE Trans. Power Delivery, vol. 12, no. 4, pp. 1717–1722, Oct. 1997.

[3] M. Noroozian, L. Angquist, M. Ghandhari, and G. Andersson, “Improving power system dynamics by series-connected facts devices,” *IEEE Trans. Power Delivery*, vol. 12, no. 4, pp. 1635–1641, Oct. 1997.

[4] L. Gyugyi, C. D. Shauder, S. L. Williams, T. R. Rietman, D. R. Torgerson, and A. Edris, “The unified power flow controller: A new approach to power transmission control,” *IEEE Trans. Power Delivery*, vol. 10, no. 2, pp. 1085–1097, Apr. 1995.

[5] F. A. Rahman and B. T. Ooi, “VSC-HVDC station with SSSC characteristic,” IEEE Trans. Power Electron., vol. 19, no. 4, pp. 1053–1059, Jul. 2004.

[6] M. Noroozijan and G. Andersson, “Power flow control by use of controllable series components,” *IEEE Trans. Power Delivery*, vol. 8, pp. 1420–1429, Jul. 1993, no.3.

[7] U. Gabriel and R. Mihalic, “Direct methods for transient stability assessment in power systems comprising controllable series devices,” *IEEE Trans. Power Syst*., vol. 17, no. 4, pp. 1116–1122, Nov. 2002.

[8] B. S. Rigby, N. S. Chonco, and R. G. Harley, “Analysis of power oscillation damping scheme using a voltage-source inverter,” *IEEE Trans. Ind. Appl.*, vol. 38, no. 4, pp. 1105–1113, Jul./Aug. 2002.

[9] M. Poshtan, B. N. Singh, and P. Rastgoufard, “A nonlinear control method for SSSC to improve power system stability,” in *Proc. Int. Conf. Power Electron., Drives Energy Syst. (PEDES’06)*, 2006, pp. 1–7.

[10] J. Xu, S. Xie, T. Tang, “ Active Damping-Based Control for Grid-Connected LCL-Filtered Inverter With Injected Grid Current Feedback Only”, IEEE Trans. Ind. Electronics, vol. 61, no. 9, pp. 4746-4758, Sept. 2014.

[11] J.C. Wiseman, B. Wu, “Active Damping Control of a High-Power PWM Current-Source Rectifier for Line-Current THD Reduction”, IEEE Trans. Ind. Electronics, vol. 52, no. 3, pp. 758-764, June. 2005.

[12] X. Wang, F. Blaabjerg, M. Liserre, Z. Chen, J. He, Y. Li, “An Active Damper for Stabilizing Power-Electronics-Based AC Systems”, IEEE Trans. Power Electron., vol. 29, no. 7, pp. 3318–3329, Jul. 2014.

[13] S. Grabic, N. Celanovic, V. A. Katic, “*Permanent Magnet Synchronous Generator Cascade for Wind Turbine Application”,* IEEE Trans. on Pow. Electron. vol.. 23, no. 3, May 2008, pp. 1136-1142.

[14] M. Vekic, S. Grabic, D. Majstorovic, N. Celanovic, V. Katic, “Ultralow Latency HIL Platform for Rapid Development of Complex Power Electronics Systems”, IEEE Trans. on Pow. El. vol.. 27, no. 11, Nov 2012, pp. 4436-4444.

[15] Grabic, N. Celanovic, and V. Katic, “Series converter stabilized wind turbine with permanent magnet synchronous generator,” in Proc. IEEE 35th Annu. Power Electron. Spec. Conf., Aachen, Germany, 2004, pp. 464–468.

[16] Marko Vekic, Milan Rapaic, Stevan Grabic Nikola Celanovic, VladimirKatic, "HIL Evaluated New Control Algorithm For PMSG Grid Connection", 17th International Symposium on Power Electronics - Ee 2013, Novi Sad, Serbia, October 30th-November 1st, 2013 Paper No. Sps-1.5, pp 1-5, ISBN: 978-86-7892-550-4

[17] Marko Vekic, “New real time emulation based procedure for Power Electronics controllers development”, PhD thesis, Faculty of technical sciences, Novi Sad, February 2014, in Serbian.