A COMPREHENSIVE PROCEDURE FOR THE DEVELOPMENT OF POWER ELECTRONICS CONTROL SYSTEMS

by

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This paper analyses several tools and methods for the comprehensive and efficient development of power electronics control systems. Hardware-in-the-loop technology enhances the possibility for compromising two opposing demands: the requirement for exhaustive testing process and the requirement for as short time to market as possible. The procedure is presented through the development and testing of a complex control algorithm connecting a d permanent magnet synchronous generator to the electrical grid. The development steps are explained and analysed in detail. Finally, several scenarios based on the presented tools and methods are proposed.

Key words: *power electronics, HIL technology, PMSM cascade, damping algorithm, development procedure*

Introduction

The cost of the controller stage is just a tiny part of the overall drive investment [1]. However, it presents its crucial part [2] since it is responsible for the safety and the overall performance. The number of tested operation points is severely limited by the safety and resource constraints as well as by the market pressure. For instance, it would be prohibitively expensive and time-consuming to test the wind turbine operation under all severe grid disturbances and short circuits [3]. On the other hand, errors and oversights which occur due to the lack of comprehensive testing might be extremely expensive. All this implies that procedures and processes should be established to find a compromise between the two opposing goals: the goal for exhaustive testing in all operational points of interest and the goal of meeting the predefined strict deadlines.

It is very difficult to fulfil this demanding task using the usual procedures based exclusively on testing in high – voltage lab. Therefore, in this paper the approach which combines the conventional processes with the simulation and hardware-in-the-loop (HIL) technology [4-6] will be presented. The proposed approach will be illustrated in detail through the development of one non-standard algorithm [7] for the connection of permanent magnet synchronous generator (PMSG) to the electrical grid. Implementation of the proposed algorithm directly on the 2 MW prototype would be extremely difficult. Therefore, this example is an excellent case study to illustrate the proposed procedure for the development and testing of PE control systems. HIL technology has particular importance in real time testing of corner

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operation points and beyond. Therefore, a fidelity verification of the employed HIL emulator needs to be performed before obtaining relevant results [8].

Combining various development tools and approaches, several comprehensive scenarios and algorithms will be introduced and briefly analysed.

Before explaining the development and testing procedure itself, we will deal shortly with the so-called active damping algorithm [9] which presents the theoretical background of PMSG synchronization. This algorithm, as already mentioned, presents a base to illustrate the power electronics comprehensive development procedure.

Active damping algorithm

It is well known from literature and practice that the connection of a synchronous machine to the grid is a more complex process than the connection of an induction machine because the vector of electromotive force (emf) has to be identical to the vector of the grid voltage. Even if the frequencies are the same, but there is still the difference between phase angles, significant oscillations in torque may occur. The oscillations are only lightly damped due to the small stator resistance. The aim of the active damping is therefore to find a way to effectively damp the oscillations so that synchronization could be successfully achieved at some arbitrary instant of time when appropriate vectors do not match. To achieve such a goal, the so-called PMSG cascade (fig. 1) is employed. The concept is described in detail in [10-12]. The original algorithm was developed for the high power, 2 MW PMSG based wind turbine.

If we apply the algorithm developed in [12], oscillations due to the rapid load change will be damped which can be concluded from the following equation:

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

where m_{el} is an electrical torque, x_s is a synchronous reactance, θ is the angle difference between vectors (phasors) of emf and voltage while u^r_{SC} stands for the reactive voltage component injected by a series converter. The first part of eq. (1) is a well-known expression which describes (in [p. u.]) the PMSG with a rounded rotor connected to the ideal grid.

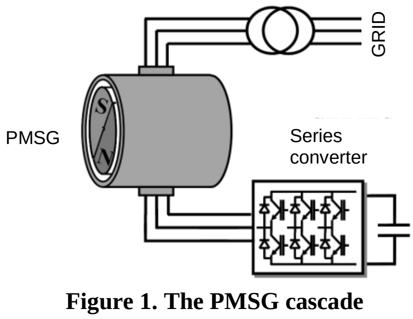


Figure 1. The PMSG cascade

Generally, this equation defines the power flow between two voltage sources coupled by the reactance (x_s here). However, the second part of the equation depends on the voltage injected by the 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 [12] that the voltage u^r_{SC} should be generated as follows:

$$u_{SC}^r = -k_{dmp}\cdot\frac{d\theta}{dt}\cdot\mathrm{sgn}(\theta) \tag{2}$$

where k_{dmp} is the damping factor and θ is the angle difference between the grid voltage and the induced PMSG emf, so-called power angle.

The control law eq. (2) needs to be modified in order to damp oscillations during the grid connection (synchronization) process. The development of the algorithm will be presented through several steps of the proposed procedure. Before explaining the procedure itself, a short overview of the employed development and testing tools will be presented.

Evaluation tools

Principally four distinctive tools are used to implement the proposed comprehensive procedure; a simulation software (Simulink), HIL emulator (where emulator Typhoon HIL400 is employed to replace the power stage), Dspace dS1104 rapid prototyping board (used as the controller stage) and a laboratory test bench. Fig. 4 shows the laboratory test bench, while fig. 2 displays HIL based set-up. The HIL set-up has a twofold role: to emulate small power test bench and original 2 MW drive. The electrical scheme of the PMSG cascade edited using Typhoon HIL software is presented in fig. 3.

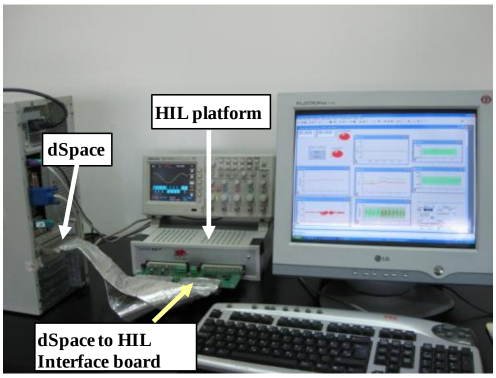


Figure 2. The HIL emulation of PMSG drive

It should be noted that the scheme in fig. 3 differs from the topology given in fig. 1 only in the sequence of series connected components whereas functionally they are equivalent.

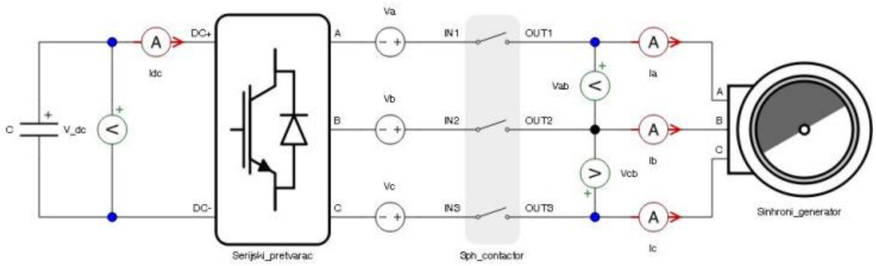


Figure 3. PMSG drive in the HIL schematic editor

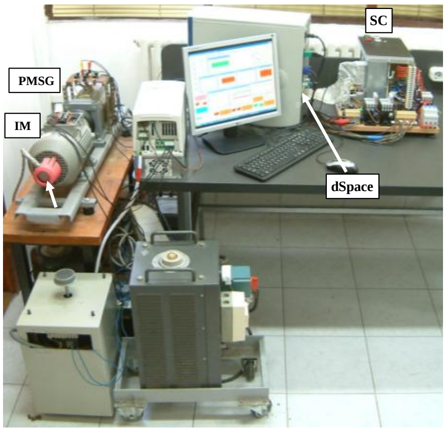
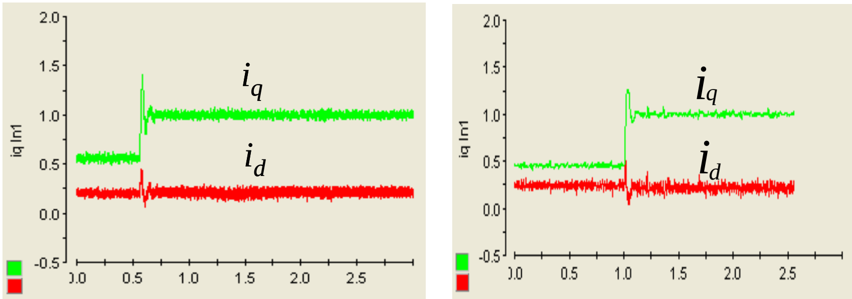


Figure 4. Laboratory test bench

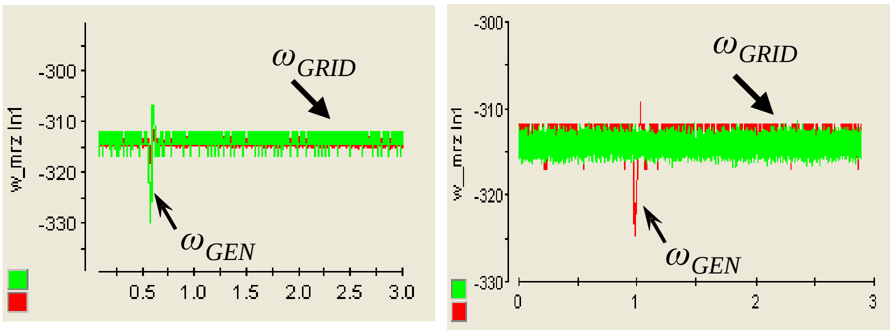
The next chapter deals with one of the crucial steps in the proposed methodology – verification of the HIL emulator fidelity, particularly regarding 2MW drive where exhaustive testing is only possible through emulation.

The HIL fidelity verification

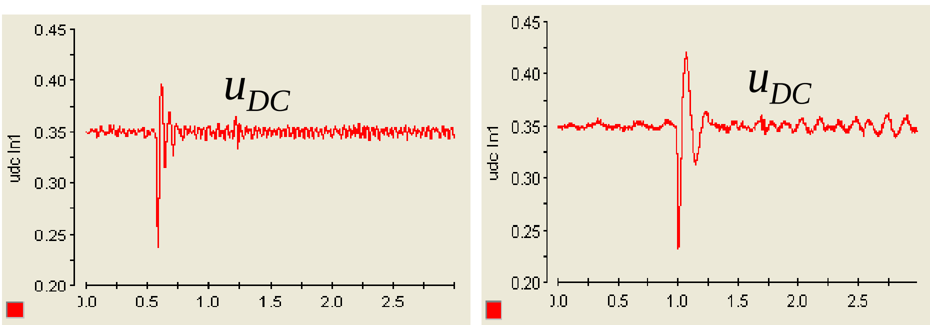
Checking of HIL fidelity verification is performed by contrasting there-out obtained results with the experimental results from the real low power (3 kW) PMSG cascade test bench (fig. 5). PMSG cascade is a very suitable comparison example because it is a highly non-linear and challenging system to emulate [13]. For the purpose of verification, two experiments were performed with two different damping factors, $k_{dmp} = 0.01$ and $k_{dmp} = 0.004$).



(a) Response of PMSG *d* and *q* stator currents in real test bench (left) and its HIL emulation (right)



(b) Response of PMSG and grid frequency in real test bench (left) and its HIL emulation (right)

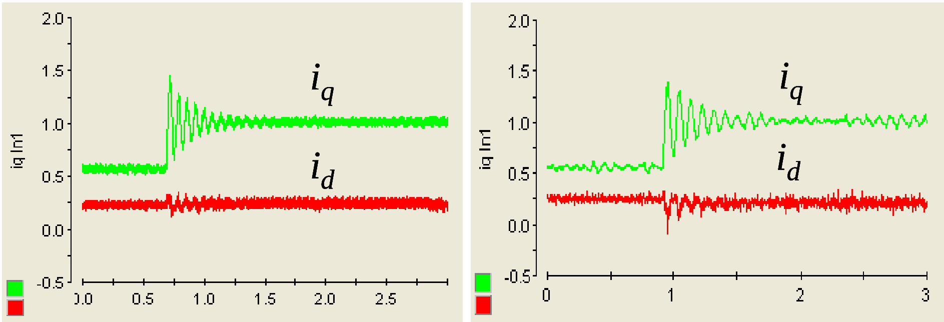


(c) Response of DC voltage in real test bench (left) and its HIL emulation (right)

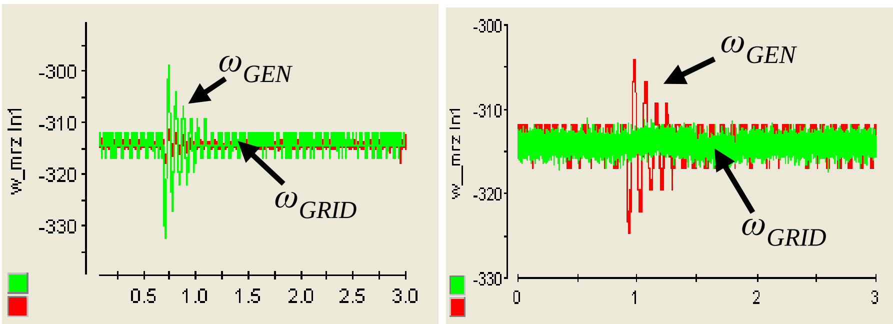
Figure 5. Real test bench and HIL emulation responses to the rapid change in the mechanical torque is performed from 0.5 to 1.0 p. u. while kdmp = 0.01

It should be noted that the reference coordinate system is set in such a way that the d axis is aligned with the rotor north-pole position, *i.e.* *q* component of the PMSG stator current is proportional to the electrical torque.

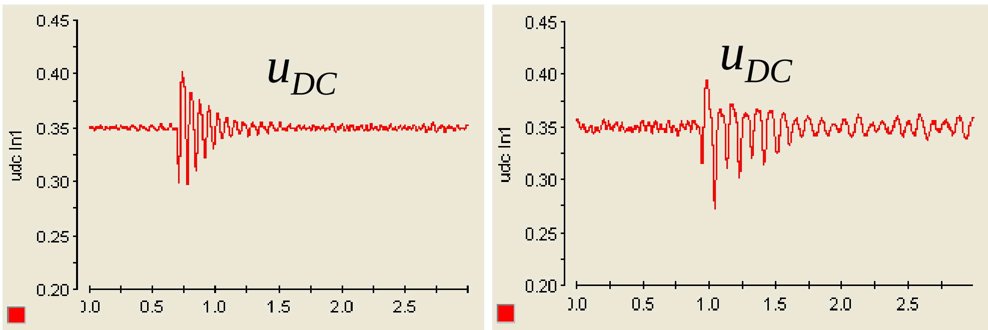
In fig. 6 the comparison was drawn for the case when the damping coefficient k_{dmp} was set to a lower value, $k_{dmp} = 0.004$.



(a) Response of PMSG d and q stator currents in real test bench (left) and its HIL emulation (right)



(b) Response of PMSG and grid frequency in real test bench (left) and its HIL emulation (right)



(c) Response of DC voltage in real test bench and its HIL emulation

Figure 6. Real HW model and HIL responses when the rapid change in mechanical torque performed from 0.5 to 1.0 p. u. while kdmp = 0.004

The results obtained in both cases show clearly a very good matching between the operation of a real PMSG cascade test bench and its HIL emulation. Minor discrepancies could be attributed to the non-modelled dynamics such as parasitic effects. Therefore, it can be concluded that the employed HIL emulator can be considered a dependable tool in the process of development and testing of PE control systems.

Development and testing procedure

Here a procedure of developing the modified active damping algorithm [14, 15] will be presented step by step using the theoretical analysis, simulation and emulation tools described in the previous chapter. The modified algorithm is based on the original active damping eq. (1) with the following additional assumptions:

- The PMSG Cascade (fig. 1) is connected to the electrical grid. The analysis considers the instant just after the synchronization.
- The series converter rated voltage is limited to 0.2 [p. u.].
- The series converter is controlled to inject reactive power only.
- The PMSG is accelerated by an external driving machine or turbine (like a wind turbine) which provides an arbitrary input mechanical torque in the range of 0.1 to 1 [p. u.] during the acceleration process, as well as after synchronization is completed.

The required algorithm will be derived, developed and tested in the following steps.

Step 1: Theory analysis

The described control law, eq. (2) has to be modified, because, at the very instant of synchronization, it cannot be assumed that PMSG speed is nominal, *i. e.* $n \neq 1$ [p. u.]. Therefore, PMSG speed appears in further consideration as a variable which also implies that the PMSG back emf also varies with n, *i. e.* $U_{EMF} = n \cdot \psi$, where ψ is a permanent magnets flux. Following these modifications, eq. (1) becomes:

$$m_{el} = \frac{\psi}{n \cdot x_s} \cdot \sin\theta - \frac{\psi}{n \cdot x_s} \cdot \sin\theta \cdot \frac{U_{SC}^r}{\sqrt{1 + n^2 \cdot \psi^2 - 2 \cdot n \cdot \psi \cdot \cos\theta}} \tag{3}$$

Accordingly, the control law, eq. (2) is now given by:

$$U_{SC}^r = -\frac{a}{2} \cdot \mathrm{n} \cdot (\mathrm{n} - 1) \cdot \frac{\sqrt{1 + \mathrm{n}^2 \cdot \psi^2 - 2 \cdot \mathrm{n} \cdot \psi \cdot \cos\theta}}{\sin\frac{\theta}{2}} \tag{4}$$

In the above equation a is the damping coefficient related to kdmp from eq. (2) as:

$$a = \frac{k_{dmp} \cdot \omega_m \cdot x_s}{\psi} \tag{5}$$

Combining eq. (4) with eq. (3), the torque expression, eq. (3) now becomes:

$$m_{el} = \frac{\psi}{x_s} \cdot \frac{\sin(\theta)}{\mathrm{n}} + a \cdot \frac{\psi}{x_s} \cdot (\mathrm{n} - 1) \cdot \cos\left(\frac{\theta}{2}\right) \tag{6}$$

In order to complete the control law, the coefficient a has to be determined. For that purpose, the control structure from fig. 7 will be employed.

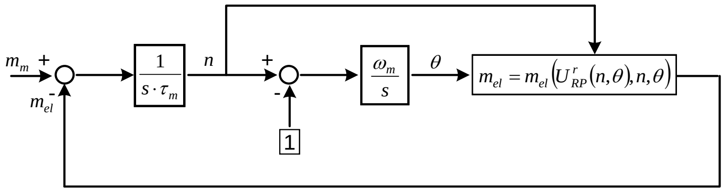


Figure 7. Synchronization control scheme

Although this control diagram looks pretty simple, the block which represents the torque calculation is non-linear as eq. (6) clearly shows. Therefore, in order to obtain the value of coefficient a, the linearization around the operation point has to be performed. The electrical torque m_{el} can be expressed as the function of the power angle and speed at the operating point (θ_0, n_0):

$$m_{el}(\theta, n) \approx m_0 + A \cdot \Delta\theta + B \cdot \Delta n \tag{7}$$

where

$$m_0 = m_{el}(\theta_0, n_0),\ A = \left.\frac{\partial m_{el}}{\partial \theta}\right|_{\theta_0, n_0},\ B = \left.\frac{\partial m_{el}}{\partial n}\right|_{\theta_0, n_0} \tag{8}$$

Variables A and B depend on the damping coefficient a, as well as the power angle θ_0 and the PMSG speed n_0 in the moment of synchronization.

It is justified to adopt the PMSG nominal value (n_0 = 1 [p. u.]) for the operation point because the process of synchronization should start when the speed approaches grid (nominal) speed. Hence, the linearized control diagram is presented in fig. 8.

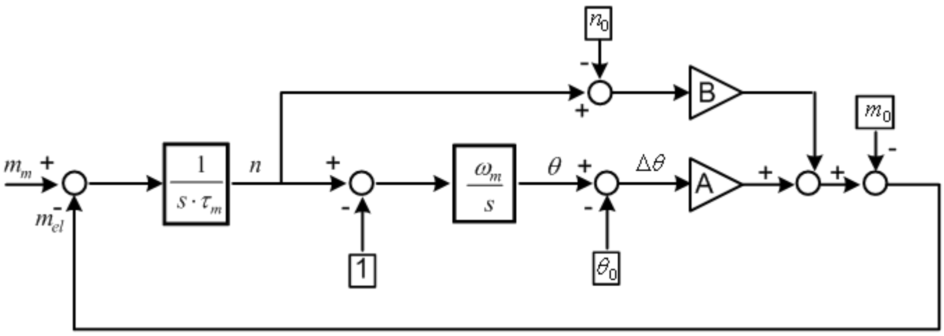


Figure 8. Linearized synchronization control scheme

Following the scheme from fig. 8, the system's characteristic equation can be obtained:

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

Therefore, with a straightforward correlation with the standard control theory, the damping coefficient and natural system frequency, ξ and ω_n, can be derived as:

$$2 \cdot \xi \cdot \omega_n = \frac{B}{\tau_m},\ \omega_n^2 = \frac{A \cdot \omega_m}{\tau_m} \tag{10}$$

Based on eq. (10) and the desired value of ξ, the damping coefficient a can be calculated.

Step 2: Algorithm feasibility

In order to determine the validity of the theoretical assumptions explained in the previous chapter, system simulations will be employed. Keeping in mind that series converter voltage is rated to 0.2 [p. u.] and injects solely reactive power, it is obvious that the proposed modified active damping algorithm has certain limits.

Indeed, the simulation results clearly show that synchronization is possible in several instances (figs. 9 and 10).

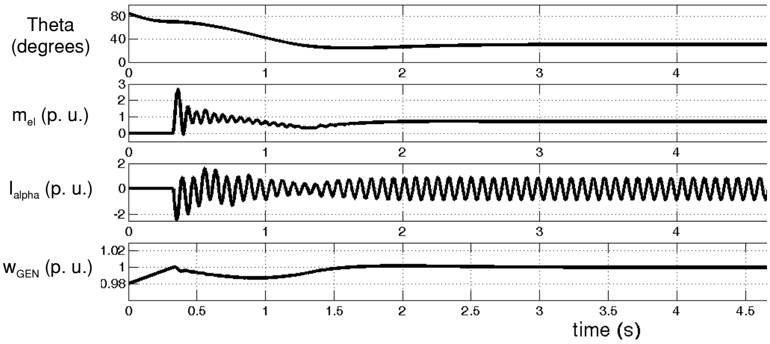


Figure 9. PMSG synchronization at rated speed n_0 = 1 [p. u.], input mechanical torque m_m = 0.7 [p. u.] and initial power angle $\theta_0 = 70^\circ$

However, it is obvious from fig. 10 that the imposed limit upon the series converter voltage $U_{SC}{}^r$ causes pronounced oscillations during the synchronization process. Therefore, it is obvious that the connection to the grid will not be possible if certain limits in the initial angle difference, shaft speed and driving torque are violated.

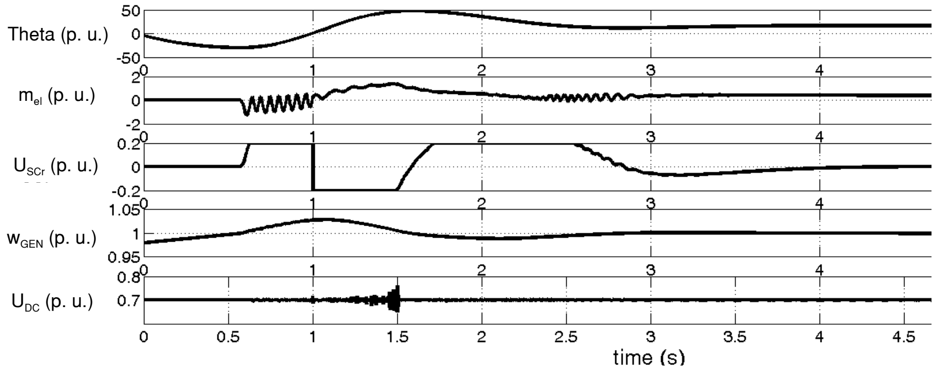


Figure 10. PMSG synchronization at rated speed n_0 = 1 [p. u.], input mechanical torque m_m = 0.4 [p. u.] and initial power angle $\theta_0 = -30^\circ$

To determine those limits, a set of expressions eq. (9)-(12) that constitute the model of the system in a quasi-steady state was employed in order to find the range of the input mechanical torque M_m, initial angle difference θ_{init} and initial speed at the beginning of synchronization n_{init}, for which the synchronization is possible.

$$U_{SC}^r = -\frac{a}{2} \cdot n_{init} \cdot (n_{init} - 1) \cdot \frac{\sqrt{1 + n_{init}{}^2 \cdot \psi^2 - 2 \cdot n_{init} \cdot \psi \cdot \cos\theta_{init}}}{\sin\frac{\theta_{init}}{2}} \tag{9}$$

$$-0,2 \le U_{SC}^r \le 0,2 \tag{10}$$

$$m_{el} = \frac{\psi}{n_{init} \cdot x_s} \cdot \sin\theta_{init} - \frac{\psi}{n_{init} \cdot x_s} \cdot \sin\theta_{init} \cdot \frac{U_{SC}^{r}}{\sqrt{1 + n_{init}^{2} \cdot \psi^{2} - 2 \cdot n_{init} \cdot \psi \cdot \cos\theta_{init}}} \tag{11}$$

$$\tau_m \frac{dn_{init}}{dt} = M_m - m_{el} \qquad \frac{d\theta_{init}}{dt} = \omega_m \cdot (n_{init} - 1) \qquad -\pi \le \theta_{init} \le \pi \tag{12}$$

The ultimate assessment of the validity of the synchronization process probes whether the power angle converges toward the steady state within the predefined time, here 5 seconds.

The results of the analysis are shown in fig. 11.

The results from fig. 7 are obtained under the assumption that the initial PMSG speed at the moment of synchronization was n_{init} = 0.98 [p. u.], while the initial power angle and input mechanical torque are arbitrary values.

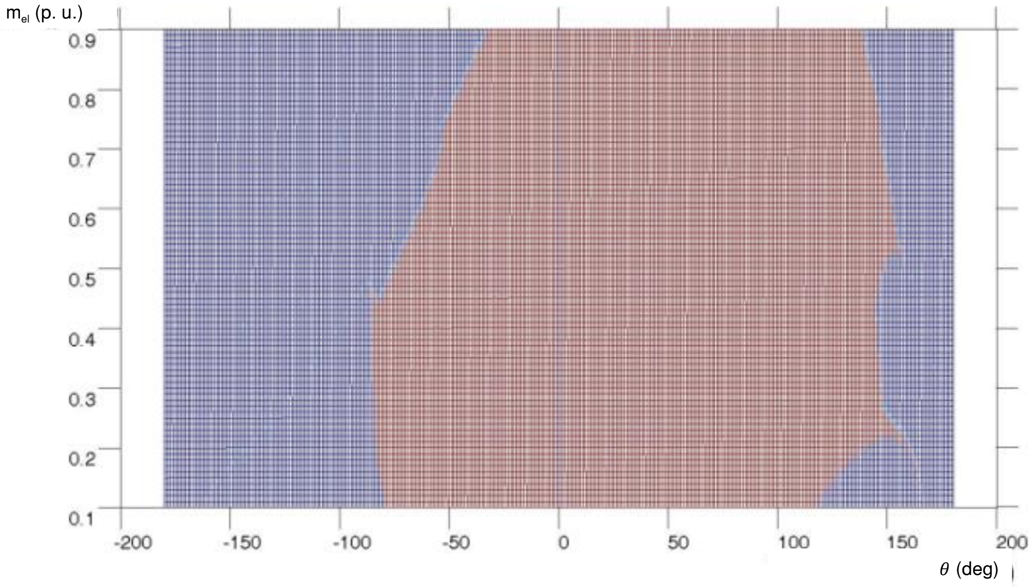


Figure 11. The area where synchronization is possible (red)

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 within the range of –30º to 110º.

Step 3: Development and testing

In order to check the control law and its effectivness, we need to perform a set of tests covering various operating points, particularly those in the borderline area. For that purpose HIL emulator (fig. 4) will be employed. The tests were performed for 60 points of interest (different input torques and initial power angle values). Here, five characteristic results will be presented, one from the deep inside area (fig. 12), two from the bordering areas (figs. 13 and 14) and two from the outside of the safe-synchronization area (figs. 15 and 16).

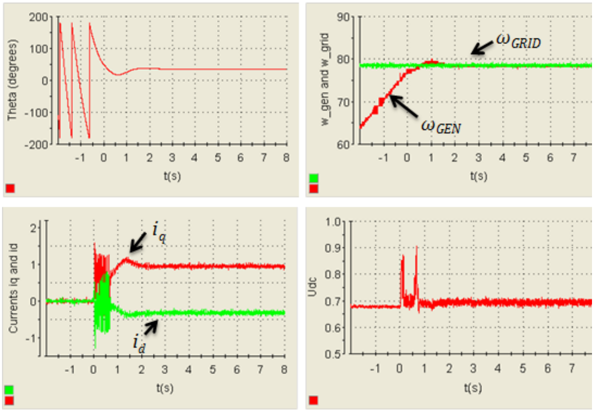


Figure 12. PMSG synchronization when M_m = 1.0 [p. u] and θ_{init} = 45°

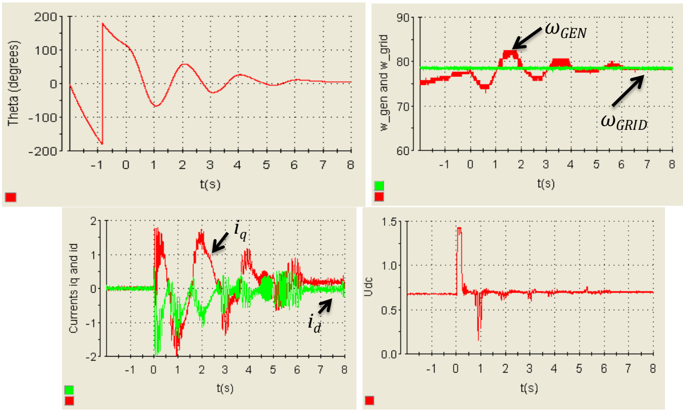


Figure 13. PMSG synchronization when M_m = 0.2 [p. u] and θ_{init} = 115°

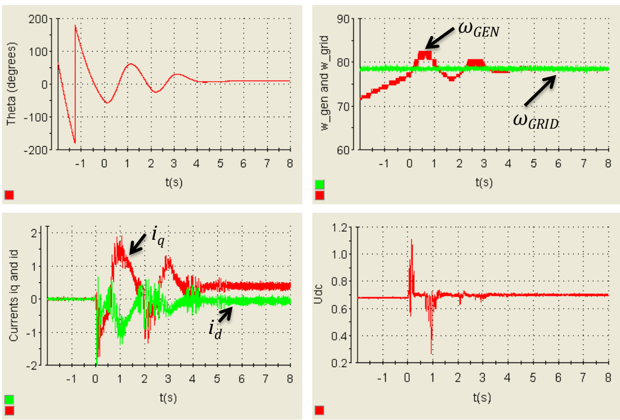


Figure 14. PMSG synchronization when M_m = 0.4 [p. u] and θ_{init} = -50°

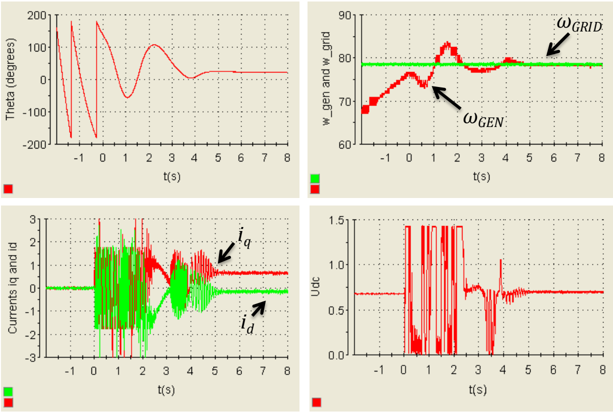


Figure 15. PMSG synchronization when M_m = 0.7 [p. u] and θ_{init} = 140°

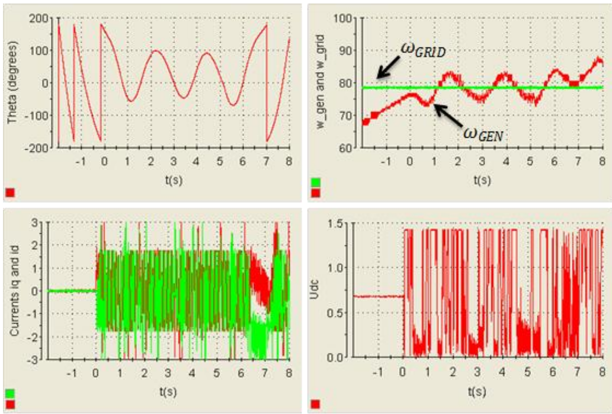


Figure 16. PMSG synchronization when M_m = 0.6 [p. u] and θ_{init} = 160°

As expected, the system response is very clear and smooth in the case shown in fig. 12. If the synchronization is performed in the border area (figs. 13 and 14), the oscillations in the PMSG shaft speed, stator currents and DC link are significantly higher but satisfactory and the connection to the grid is considered successful. In the case shown in fig. 15, although the synchronization has been accomplished, high and intolerable oscillations of torque and DC bus voltage occur, which would not be acceptable in the real drive. Finally, fig. 16 clearly shows that the synchronization to the grid is impossible when the initial angle difference is significantly outside the pre-defined safe boundaries (the red area in fig. 11). It can be concluded that thorough HIL emulation confirmed the validity of the proposed connection algorithm in the pre-defined borders.

Development scenarios

Based on the presented procedure steps, several scenarios or algorithms for the comprehensive PE control systems development can be proposed [7]. For the sake of clarity, the algorithm of the conventional development will be given first (fig. 17).

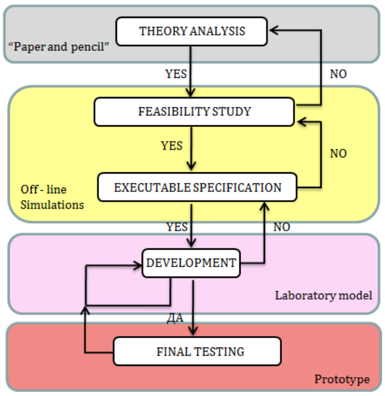


Figure 17. Classical development algorithm

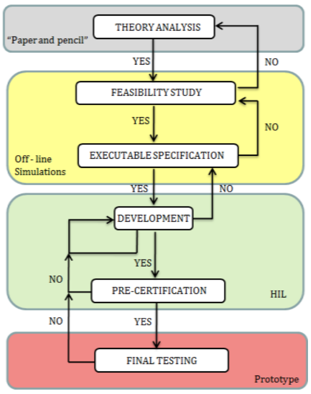


Figure 18. Combined development algorithm

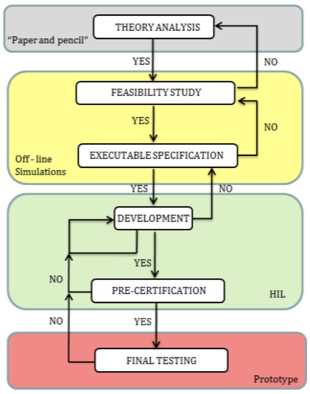


Figure 19. Development algorithm based on HIL

The key step in this scenario is performed on the laboratory test bench. The main drawback of such approach is the very long time constant of the inner development loop.

The employment of HIL technology leads to the algorithm depicted in fig. 18. The development time constants are comparatively small and the whole process is much more efficient.

If in the initial stages of the PE control development project the interface between the controller stage and the emulator is compatible, *i. e.* if it is not necessary to invest the additional effort to solve this issue, the emulator can be used instead of the simulation software. This approach offers the possibility of the following development algorithm (fig. 19).

It is possible to establish a variety of scenarios (algorithms) based on the specific PE control development project needs. All these algorithms are founded on the key steps described in detail in the section *Development and testing procedure* section taking into account the advantages and drawbacks of each particular tool and method. Finally, there is one interesting and important consequence of employing the algorithm from fig. 18 and particularly fig. 19. Namely, HIL emulation can be automated, thus further increasing the number of tested operation points. In the presented development algorithms, this means that HIL loop (the green one) executes automatically in a very short time which implies a very high efficiency of the overall development process. Such approach opens the possibility for the so-called *pre-certification* where the system control design is practically verified and ready for the final system integration.

Conclusions

The development of PE control systems meets two opposing challenges: on the one hand, there is a demand for exhaustive testing, ideally in all operation points including potentially dangerous situations and, on the other hand, we have a demand for the short time to market. HIL technology enhances overall testing possibilities by reducing the complexity of the power stage to the software level while maintaining the real time execution. Since HIL emulator has an important role in the process, it needs to be verified by a comparison with the results obtained from the real physical system. The paper analysed synchronization control of PMSG cascade which is a rather demanding example due to its high non-linearity.

The proposed procedure was demonstrated through several steps: theory analysis, feasibility, development and testing. To illustrate all the steps in detail, a modified control strategy for connecting PMSG to electrical grid was chosen, implemented and tested. Based on these results and conclusions, two scenarios of comprehensive development procedure were proposed.

Acknowledgment

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