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Start-Up of Virtual Synchronous Machine: Methods and Experimental Comparison

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Abstract—**A modern grid is smarter mainly in the advance in information and communication technologies, while the power processing mechanism does not make a big difference. To make a modern grid smarter, the grid control should be improved to process the power in a smarter way. Therefore, it is easily foreseen that virtual synchronous machines, which emulates the synchronous machines based on power converters, may have big potentials in a future energy internet. This paper uses the Synchronous Power Controller with emulated and improved synchronous machine characteristics for renewable generation systems and proposes two start-up strategies. The proposed strategies are explained in detail, verified and compared by experimental results.**

Keywords—DC-AC power converter, Grid connection, Power converter control, Virtual synchronous machine.

I. Introduction

Interconnecting different forms of energy through an electrical grid, known as energy internet, has been an idea increasingly accepted by people, which is pushed by the large-scale penetration of renewables in modern grid. Power converters, which become energy routers in energy internet, play an important role. Further, control of grid-connected power converters is fundamental and critical for a good operation of the grid or the energy internet.

Traditionally, grid-connected power converters process power in a different way compared with a synchronous machine. The main control mechanisms for grid-connected power converters are based on the phase-locked loop (PLL), the instantaneous active and reactive power control and the maximum power point tracking (MPPT). As a way giving more considerations to the grid stability, virtual synchronous machine (VSM) [1] is developed rapidly, in both theory and practice, in recent years.

The recent studies on VSM have been conducted from different perspectives like inertia emulation [2], [3], PLL-less control [4], providing virtual impedance [5], [6], adaptive inertial response [7], [8], primary frequency and voltage control [9], stability analysis [10].

Despite the above literatures that work on different aspects of VSM (mostly inertia emulation), the start-up method is not explained. There have been many results presented previously to show how VSMs show different characteristics compared with conventional grid-connected power converters, and further contribute to grid frequency stability. However, there has not been much details provided to explain how a power converter controlled by these methods is started and connected to the grid.

Due to a difference in magnitude and phase-angle between the inner voltages (virtual electromotive force) of the VSM and the grid voltages, there will be a big transient current flowing between the power converter and the grid, at the instant when the converter is connected to the grid (when the control pulses are enabled). The transients caused by an abrupt switch-in of a generation unit could harm sensitive equipment or disturb other users of the network. It is necessary to take measures for a smooth start-up of a VSM. Besides, the start-up performance is an inevitable part for justifying the feasibility of a proposal and certifying a generator.

This paper explains in detail the method for the start-up of a VSM. Firstly, the Synchronous Power Controller (SPC) with emulated and improved characteristics of synchronous machines for grid-connected power converters is introduced, and further the start-up strategies based on the SPC itself is presented. No dedicated synchronization unit is needed during the start-up process based on the proposed methods. Two different methods are proposed and explained in detail, respectively the pre-synchronization method and the virtual admittance conditioning method, which are supported by the experimental comparison.

II. Synchronous Power Controller Based VSM

The Synchronous Power Controller (SPC) endows grid connected voltage source converters (VSC) with virtual electromechanical characteristics, as an emulation and enhancement of synchronous generators [11]. The overall control architecture of the SPC-based VSM is shown in Fig. 1.

The power loop controller (PLC) and the virtual admittance determine the main characteristics of the SPC, which correspond to the mechanical and electrical part of synchronous machines, respectively. The PLC commonly provides the inertia and damping characteristics, and the virtual admittance emulates the stator output impedance of a synchronous machine.

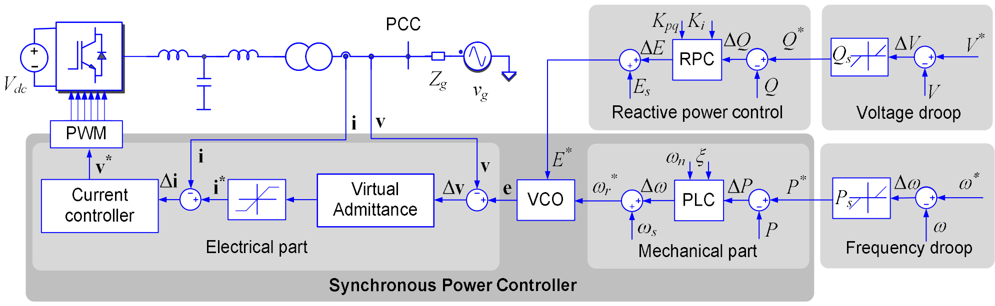


Fig. 1. Grid-connected power converter based on the Synchronous Power Controller (SPC).

The electromechanical characteristics of synchronous generators can be split into two aspects, the stator output impedance (electrical) and the rotor inertia (mechanical). The former one defines the fundamentals of the electrical interaction between the converter the grid in terms of active and reactive power exchange, which also contributes to the grid synchronization, power sharing and unbalance compensation. The latter one defines the power-frequency dynamics in power systems and contributes to the frequency stabilization.

The active and reactive powers transferred from e to v through a line with an impedance is defined as, [40]:

$$P = \frac{EV}{Z}\cos(\phi-\delta) - \frac{V^2}{Z}\cos(\phi), \quad (1)$$

$$Q = \frac{EV}{Z}\sin(\phi-\delta) - \frac{V^2}{Z}\sin(\phi), \quad (2)$$

where E and V are the rms of e and v, $Z\angle\phi$ the line impedance between the two sources, and δ the phase-angle difference between e and v, and it is known as load-angle.

For common synchronous machines, considering a mainly inductive output impedance and a synchronized condition (a small value of δ), (1) and (2) can be simplified as:

$$P = \frac{EV}{X}\delta = P_{\max}\delta, \quad (3)$$

$$Q = \frac{V(E-V)}{X}. \quad (4)$$

As shown in (3) and (4), synchronous machines regulate the active and reactive powers by adjusting the load-angle and the magnitude of the electromotive force through the governor and the exciter, respectively. Similarly, the SPC controls the active and reactive powers by adjusting its inner voltage phase-angle and magnitude, respectively, similar to a synchronous machine, rather than the conventional in-phase and in-quadrature current control performed in the decoupled rotating (d-q) reference frame.

III. START-UP STRATEGIES FOR VSM

Conventional synchronous machines are enabled and connected to the grid only after a synchro-scope has shown the frequency and the phase of the machine are the same as those of the grid. The flexibility of the SPC allows avoiding the undesired transients without having to rely on long synchronization processes.

Two start-up methods are presented in this section.

A. Pre-synchronization method

If one considers a virtual active and reactive power injection assuming that the reference current is the real current flowing through the virtual admittance, it is possible to synchronize the SPC to the grid before enabling the converter. Fig. 2 shows the procedure of the start-up based on the proposed pre-synchronization method.

To start synchronization, the power calculation block takes the reference current instead of the measured current. The synchronization starts once the action 1 is taken as shown in Fig. 2. At this stage, the converter is blocked by disabling the PWM pulses, and some control parts are also disabled such as the current controller and droop controllers.

Then the internal voltage **e** will be rapidly regulated to be synchronized with the grid voltage **v**. During the synchronization process, the internal variables are modified as in normal operation, but this does not cause any disturbance in the power system because the converter is blocked. Only virtual values of active and reactive power are used, so the acceleration or deceleration of the SPC does not require an actual exchange of power.

To check whether the synchronization is completed, one can define a given power tolerance S_t and check if the virtual apparent power injected by the converter S is below this tolerance and lasts longer than a given time T_a. When the above two conditions are met, the action 2 shown in Fig. 2 will be taken. This action contains enabling the converter, current

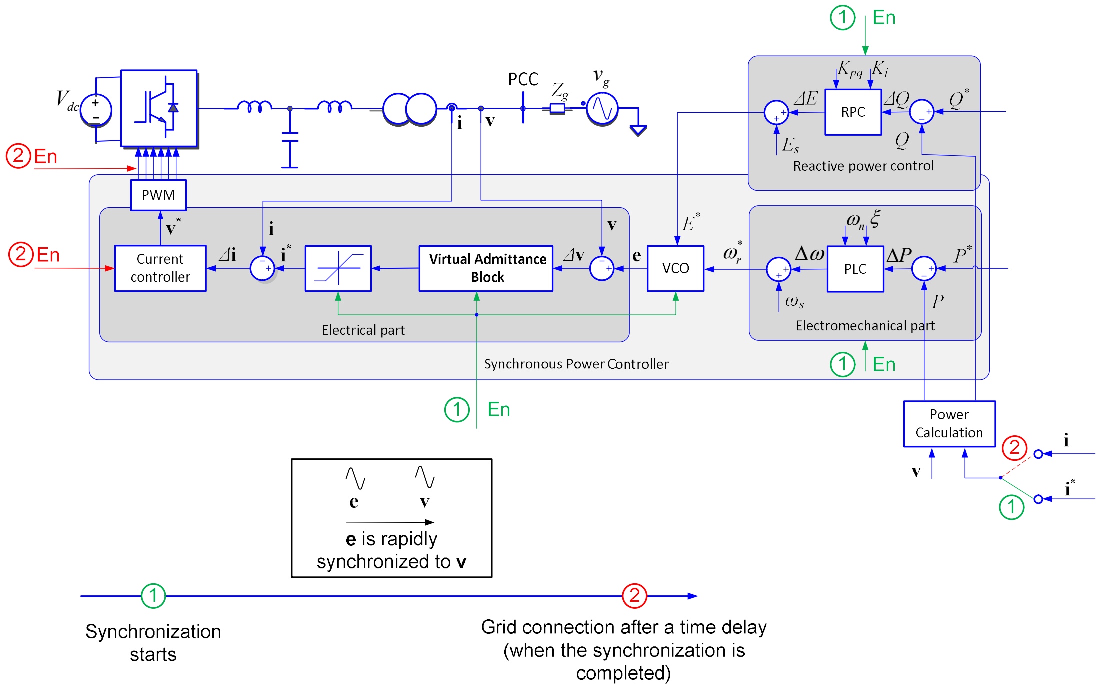


Fig. 2. The pre-synchronization start-up strategy for a SPC-based power converter.

controller, droop controllers and replacing the current reference with the measured current for the power calculation block.

In summary, this method has two steps:

1. The measured active and reactive power are calculated using the current reference, as if they are the measured current, and these calculated powers will be referred as the virtual powers. The virtual admittance, power loop controller and reactive power controller are enabled.

2. When the synchronization condition is met, or a fixed time delay after the first step, the switching of the power converter and the inner current control loop are enabled. In the meantime, the real measurement of the current is used, substituting the current reference, to calculate the active and reactive powers.

B. Virtual admittance conditioning method

During a connection process, it is possible to increase the virtual impedance so that the current injected by the converter is effectively limited. Once the connection is done, the virtual impedance is set back to its normal operation values. However, the restoration of these values must be handled with care, because it generates a transient if it is done abruptly, as any sudden topological change would do.

By a proper conditioning of the inductance and resistance of the virtual admittance, a smooth start-up and grid connection can be achieved. This method can be divided into 3 steps:

1. To limit the current transient at the moment of connecting the power converter to the grid, the initial values for virtual inductance and resistance are set significantly greater than the nominal ones;

2. After the grid connection is done and settled, the values of the inductance and resistance start to be reduced gradually to their nominal values;

3. Once the nominal values are reached, the converter can operate normally and increases the active power injection to its nominal value.

IV. EXPERIMENTAL RESULTS

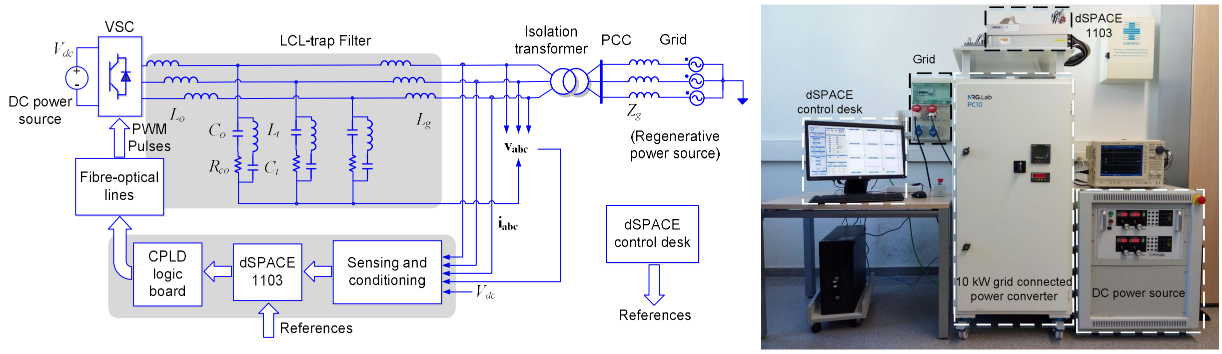
The experimental setups are shown in Fig. 3, where a 10 kW converter interacts with the grid that is formed by the regenerative power source California Instrument MX45. By using this ac source, the grid voltage waveforms, magnitude and frequency are programmed, and hence the sweep of grid frequency can be generated. A 20 kW dc power source supplies the dc bus of the converter, and the control is implemented in dSPACE ds1103. The parameters are shown in Table I. The lead lag controller is choses as the power loop controller for experimental tests.

Table I. Key experimental parameters for SPC-based VSM

Description	Symbol	Value
grid phase-to-phase voltage	V_g	400 [V]
grid nominal frequency	f_g	50 [Hz]
dc bus voltage	V_{DC}	640 [V]
power converter nominal power	P_N	10 [kW]
switching frequency	f_{sw}	10050 [Hz]
virtual resistance	R_{pu}	0.1 [p.u.]
virtual reactance	X_{pu}	0.3 [p.u.]

A. Pre-synchronization method

In the first case, a lead-lag power loop controller is used for the SPC, with the damping coefficient $\xi = 0.7$, inertia constant H = 5 s, and frequency regulating ratio D_P = 2 kW/Hz. The

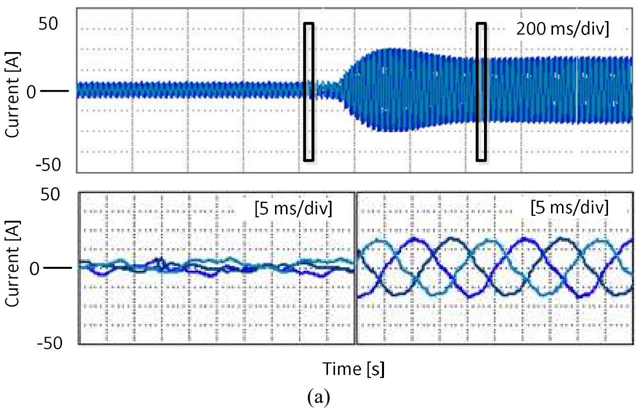


(a) (b)

Fig. 3. 10 kW grid-connected power converter experimental setup: (a) block diagram, (b) laboratory view.

events are E1, E2 and E3, where E1 is the instant when the pre-synchronization starts, E2 is the instant when the grid is connected, which is 0.5 s after E1, and E3 is the instant when the power steps from 0 to 9 kW and 2 kVar, which is 0.1 s after E2.

The results are shown in Fig. 4, where only a small transient power is observed when E2 happens. Active and reactive power step up smoothly and are controlled accurately.



(a)

(b)

Fig. 4. Start-up of a SPC-based VSM using the pre-synchronization method, ζ = 0.7: (a) currents injected to the grid, (b) active and reactive powers.

In the second case, a lead-lag power loop controller is used for the SPC, with the damping coefficient is changed to $\xi = 0.9$, inertia constant is changed to $H = 2$ s, and frequency regulating ratio $D_P = 2$ kW/Hz. The events are E1, E2 and E3, where E1 is the instant when the pre-synchronization starts, E2 is the instant when the grid is connected, which is 0.5 s after E1, and E3 is the instant when the power steps from 0 to 10 kW and 2.5 kVar, which is 0.1 s after E2.

The results are shown in Fig. 5, where only a small transient power is observed when E2 happens. Like the case shown in Fig. 4, no transient is observed when E1 happens, thanks to the fact that the converter is not enabled and connected to the grid when the pre-synchronization starts. Active and reactive power step up smoothly and are controlled accurately, as well as the case shown in Fig. 4.

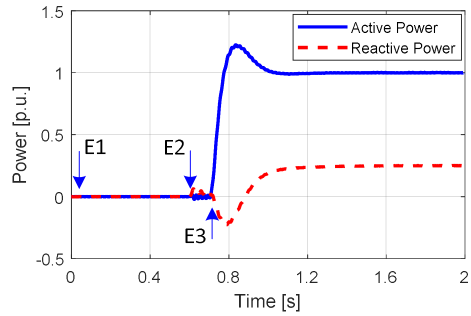


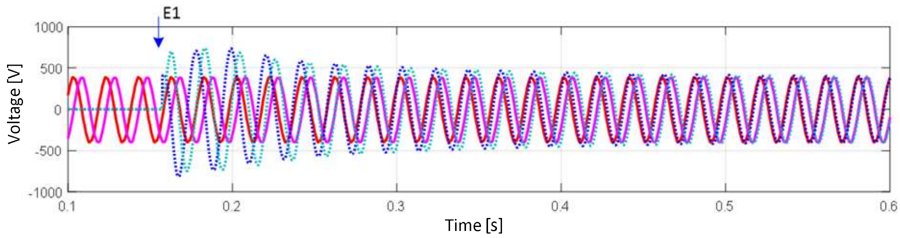
Fig. 5. Start-up of a SPC-based VSM using the pre-synchronization method, ζ = 0.9: (a) currents injected to the grid, (b) active and reactive powers.

The results for the above two cases showing the measured grid voltages and the inner voltages (virtual electromotive force) are given in Fig. 6. It is shown in Fig. 6(a) that in the first case, E1 happens around t = 0.15 s, and the pre-synchronization is completed in less than 0.5 s, being ready for the event E2. Fig. 6(b) shows the profiles for the first case during power step-up. It is shown in Fig. 6(c) that in the second case, E1 happens at t = 0.1 s, and the pre-synchronization is also completed in less than 0.5 s, being ready for the event E2.

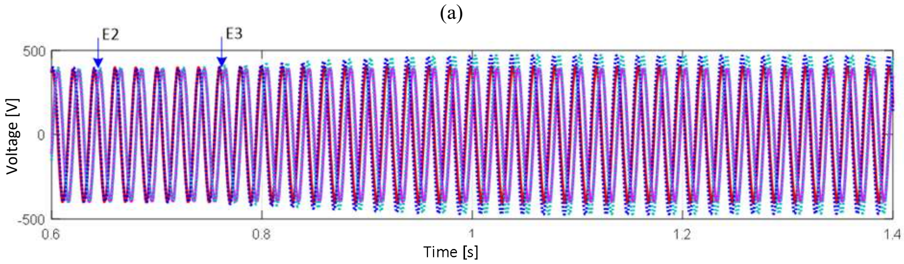
B. *Virtual admittance conditioning method*

In this case, also a lead-lag power loop controller is used for the SPC, with the damping coefficient $\xi = 0.9$, inertia constant $H = 4$ s, and frequency regulating ratio $D_P = 4$ kW/Hz. The events are E1, E2 and E3, where E1 is the instant when the grid is connected, E2 is the instant when the virtual inductance and resistance values start changing, which is 0.1 s after E1, and the values are conditioned exponentially to the nominal values during 0.5 s, and E3 is the instant when the power steps from 0 to 10 kW and 2.5 kVar, which is 0.7 s after E1.

The results are shown in Fig. 7. Only a small transient power is observed when E1 and E2 happen. Active and reactive power step up smoothly and are controlled accurately.



(a)



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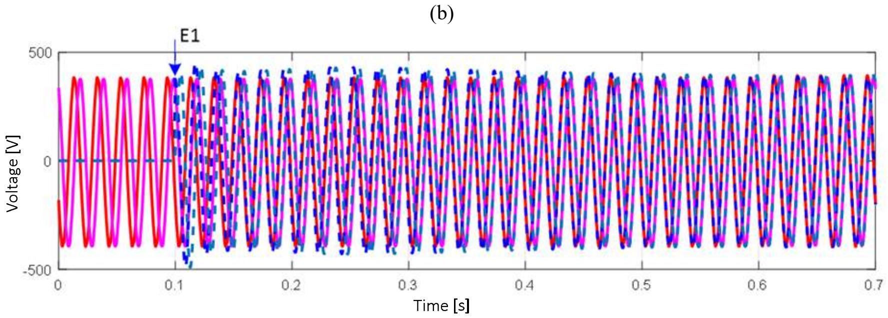
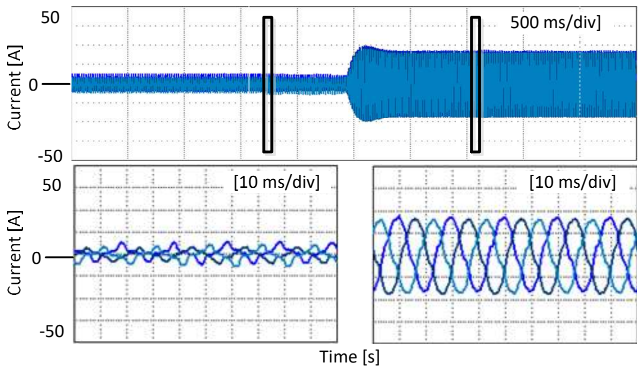
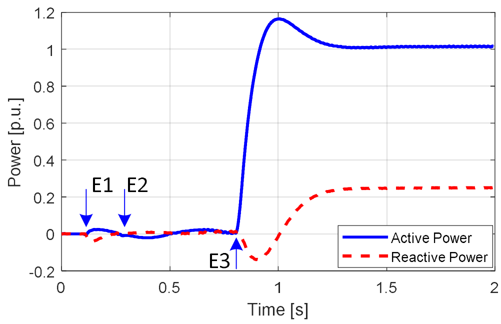


(c)

Fig. 6. Measured voltages **v** (dash) and virtual electromotive force **e** (dot) on stationary reference frame, start-up of a SPC-based VSM using the pre-synchronization method: (a) $\zeta = 0.7$, pre-synchronization process, (b) $\zeta = 0.7$, power step-up, (c) $\zeta = 0.9$, pre-synchronization process.



(a)



(b)

Fig. 7. Start-up of a SPC-based VSM using the admittance conditioning method: (a) currents injected to the grid, (b) active and reactive powers.

The results for this case showing the measured grid voltages and the inner voltages (virtual electromotive force) are given in Fig. 8. It is observed that E1 happens at t = 0.1 s, and the pre-synchronization is completed in less than 0.15 s, being ready for the event E2.

C. Comparison

Both methods are compared, with the same control setting, where a lead-lag power loop controller is used for the SPC, with the damping coefficient $\xi = 0.9$, inertia constant $H = 4$ s, and frequency regulating ratio $D_P = 2$ kW/Hz.

The events for the pre-synchronization method are E1, E2 and E3, where E1 is the instant when the pre-synchronization starts, E2 is the instant when the grid is connected, which is 0.5 s after E1, and E3 is the instant when the power steps from 0 to 10 kW and 2.5 kVar, which is 0.1 s after E2.

The events for the virtual admittance conditioning method are Ea, Eb and Ec, where Ea is the instant when the grid is connected, Eb is the instant when the virtual inductance and resistance values start changing, which is 0.1 s after Ea, and the values are conditioned exponentially to the nominal values during 0.5 s, and Ec is the instant when the power steps from 0 to 10 kW and 2.5 kVar, which is 0.7 s after Ea.

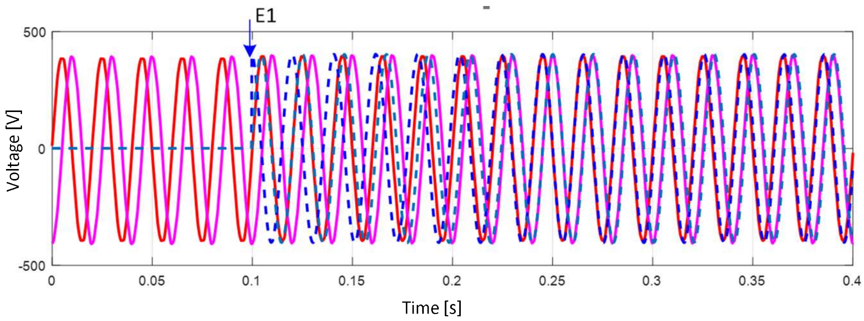


Fig. 8. Measured voltages **v** (dash) and virtual electromotive force **e** (dot) on stationary reference frame, start-up of a SPC-based VSM using the admittance conditioning method.

The results are shown in Fig. 9. It is observed that both methods result in small transient during the grid connection and smooth step-up of the active power. The pre-synchronization method presented a shorter time for start-up and a smaller transient in grid connection.

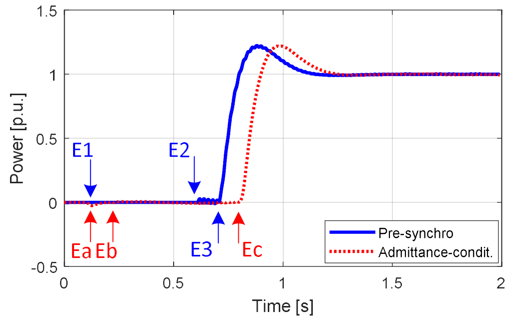


Fig. 9. Active powers injected, start-up of a SPC-based VSM comparing both methods.

V. Conclusion

For the virtual synchronous machine, two start-up methods were proposed and explained in detail in this paper based on the Synchronous Power Controller. Experimental results demonstrated the effectiveness of both methods. It has been demonstrated in different scenarios that the SPC-controlled power converter can start-up during less than 1.5 s, which is sufficient for pre-synchronization, grid connection and power step-up. The pre-synchronization method is as good as the virtual admittance conditioning and is even faster.

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