Operation Analysis and Determination of Virtual Synchronous Machine Model Parameters

Nikola Krstić, Milutin Petronijević, Filip Filipović

Abstract **–This paper presents the concept, model and simulation of virtual synchronous machine (VSM) operation and proposes a methodology for its parameter values selection. VSM was synchronized to the grid and its responses to given references of active and reactive powers were obtained, for different values of VSM parameters. Responses of grid-feeding and grid-supporting model of VSM, were considered. Special attention is paid to the formation of control loops for active and reactive power as basic structures in the VSM operation. Based on these control loops, values of VSM parameters are determined by pole adjustment method, which was the basic task of this paper. VSM model and the model of used power grid were made in Matlab/Simulink, in which results presented at the end of the paper, were generated.**

Keywords – **virtual synchronous machine, power converter, control loop, emulation.**

I. INTRODUCTION

Increased distributed generation, presence of renewable energy sources, as well as the emergence of microgrids in the power system, have led to new ideas and concepts to appear [1]. Many of these concepts include the use of power electronics to increase the flexibility and range of power grids, and one of them is virtual synchronous machine (VSM). This concept arose from the need to bring the operation of three-phase power converters closer to the operation of synchronous machines [2], primarily by introducing virtual inertia. Doing this, the control operation of energy converters has not changed significantly, and it is still based on droop control (which is inherited from synchronous machines), but now a certain inertia is included in it. Addition of inertia, which emulates moment of inertia of the rotor of synchronous machine and the inertia of inductance in excitation circuit, increases stability of the grid and its resistance to various types of disturbances and power imbalances [3]. This is especially important in grids where large proportion of generated power comes from power sources connected via power converters [4].

In this paper, structure and concept of operation of VSM model [3],[5],[6] are presented first, where the equations of mathematical model of synchronous machine, that is going to be emulated with VSM, are written. After that, the methodology for determining the values of VSM parameters was presented. It is clear that values of VSM model parameters will largely determine its response [7] to the given references, which is why their proper selection, in order to meet a particular requirement, is the main task of this paper. In order to make this possible, VSM model was decomposed into two basic structures, one includes active power-frequency regulation, and the other reactive power-voltage regulation [5]. In this way, control loops for active and reactive power are formed in the paper, on the basis of which values of VSM parameters are determined, using pole adjustment method. Number of these parameters differs in the case of grid-feeding and grid-supporting model of VSM, that depends on the role which energy converter have in the grid [8]. Grid-feeding energy converter only meets power requirements regardless of the grid voltage and frequency, while grid-supporting one, in addition to that, supports regulation of voltage and frequency in the grid. That is way, in this paper, two additional coefficients in the grid-supporting model of VSM are used, one for grid voltage and the other for grid frequency control. Three basic parameters, common to both VSM models, are: moment of inertia, damping factor and ratio coefficient of reactive power to change of excitation flux [3]. In this paper, VSM is connected to the grid via LCL filter and the grid is modeled by real voltage generator.

Results presented at the end of the paper contain responses of certain quantities, for different values of parameters [9] in VSM model for grid-feeding and grid-supporting structure.

II. VSM MODEL

Basic idea behind the concept of VSM is to create an emulator which will ensure that three-phase power converter behaves like a synchronous machine towards the grid. That is, it is necessary to equalize voltages at the end of the power converter with electromotive forces that would occur in the operation of a synchronous machine. Since the electromotive forces in synchronous machine are determined by the first derivative of excitation flux, it is clear that VSM model must take into account relations for excitation flux and angular frequency. In this paper, mathematical model of synchronous machine with cylindrical rotor and without losses, is used to form VSM model. Excitation flux through the phase windings of synchronous machine is given by equations:

$$\psi_{fA} = \psi_{fm}\cos(\omega t) \tag{1}$$

$$\psi_{fB} = \psi_{fm}\cos(\omega t - \tfrac{2\pi}{3}) \tag{2}$$

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$$\psi_{fC} = \psi_{fm}\cos(\omega t + \frac{2\pi}{3}) \qquad (3)$$

Based on excitation flux, electromotive forces in phase windings are determined according to the vector equation:

$$\vec{e}_f = -\frac{d\vec{\psi}_f}{dt} \qquad (4)$$

Based on (4), electromotive forces in phase windings can be obtain using equations:

$$e_{fA} = \omega\psi_{fm}\sin(\omega t) - \frac{d\psi_{fm}}{dt}\cos(\omega t) \qquad (5)$$

$$e_{fB} = \omega\psi_{fm}\sin(\omega t - \frac{2\pi}{3}) - \frac{d\psi_{fm}}{dt}\cos\left(\omega t - \frac{2\pi}{3}\right) \qquad (6)$$

$$e_{fC} = \omega\psi_{fm}\sin(\omega t + \frac{2\pi}{3}) - \frac{d\psi_{fm}}{dt}\cos\left(\omega t + \frac{2\pi}{3}\right) \qquad (7)$$

Angular frequency of VSM appearing in (1)-(7) is found by motion equation of rotor of VSM:

$$\frac{d\omega}{dt} = \frac{1}{J}(\frac{P_{set}}{\omega} - \frac{P}{\omega} - D_p(\omega - \omega_G)) \qquad (8)$$

Where: J −moment of inertia of rotor of VSM, ω −angular frequency of VSM, ω_G −angular frequency of the grid, D_p −damping factor, P_{set} −active power reference (generated mechanical power), P −active power injected into the grid by VSM (active power of consumption).

It must be noted that in (8) generated mechanical power of VSM is identified as active power reference and generated active power is identified as active power injected into the grid. This identifications can be done because model of VSM emulates synchronous machine without losses and active power losses in LCL filter are negligible. In addition to the angular frequency, it is necessery to determine the intensity of excitation flux in VSM. This is done on the basis of excitation regulation in synchronous machine, using reactive power eror:

$$\frac{d\psi_f}{dt} = D_q(Q_{set} - Q) \qquad (9)$$

Where: ψ_f −excitation flux in phase windings of VSM, D_q −ratio coefficient of reactive power to change of excitation flux, Q_{set} −reactive power reference, Q −reactive power injected into the grid by VSM.

Based on (5)-(9), grid-feeding model of VSM is formed in Matlab/Simulink. In the case of grid-supporting model, additional links for grid voltage and frequency regulation must be considered. In this paper, grid is modeled with real voltage generator whose equivalent impedance has big *R/X* ratio, that is usually the case in low voltage networks. This would mean that the grid voltage regulation in the point of connection of VSM to the grid is most efficiently achieved using injected active power. On the other hand, the best way to regulate grid frequency in the point of connection is injecting reactive power. This is based on the voltage drop formula between node *i* and node *j* connected with branch containing active resistance *R* and reactance *X*, when active power P_{ij} and reactive power Q_{ij} flows from node *i* to node *j*.

$$U_i - U_j = \frac{P_{ij}R + Q_{ij}X}{U_i} + j\frac{P_{ij}X - Q_{ij}R}{U_i} \qquad (10)$$

Considering (10), in R dominant type of grids, voltage in connection point (U_i) is increased when injected active power (P_{ij}) is increased, and the phase ange (frequency) is increased when injected reactive power (Q_{ij}) is decresed [1],[8]. Considering this, for grid-supporting model, (8)-(9) become:

$$\frac{d\omega}{dt} = \frac{1}{J}(\frac{P_{set} - P + K_V(V_{ref} - V_G)}{\omega} - D_p(\omega - \omega_G)) \qquad (11)$$

$$\frac{d\psi_f}{dt} = D_q(Q_{set} - Q - K_\omega(\omega_{ref} - \omega_G)) \qquad (12)$$

Where: V_G −grid voltage, V_{ref} −grid voltage reference, K_ω −control coefficient of grid angular frequency, K_V −control coefficient of grid voltage, ω_{ref} −grid angular frequency reference.

Signals of obtained electromotive forces given by (5)-(7) are used to generate voltage at the end of the energy converter, what can be seen in Fig. 1, where grid-supporting model of VSM is presented, as more general one.

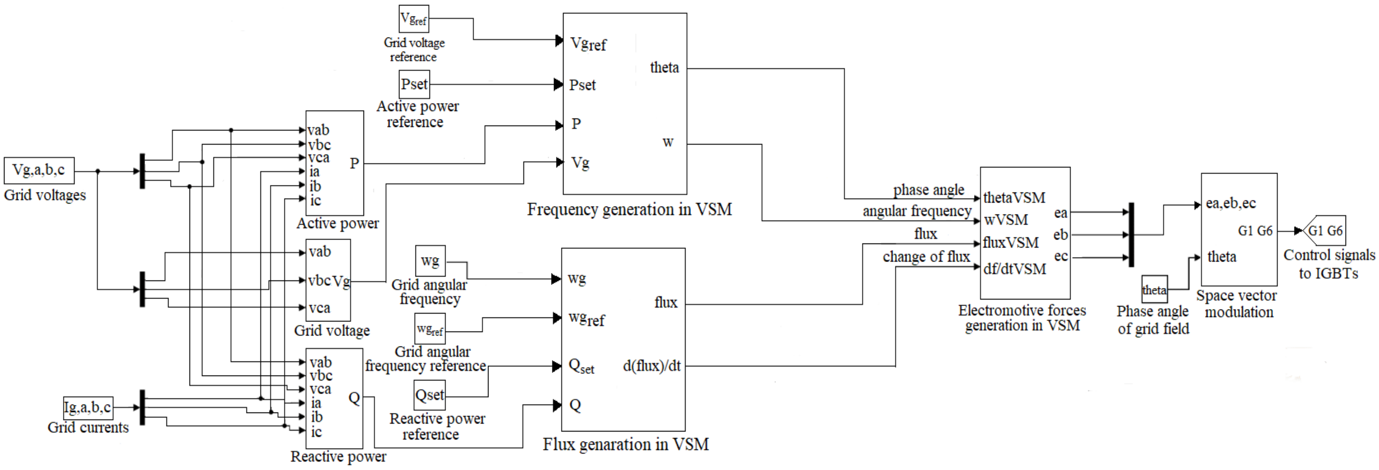

Fig. 1. Block diagram of grid-supporting model of VSM

III. FORMATION OF CONTROL LOOPS AND VSM PARAMETER DETERMINATION

In order to determine the parameters in VSM model, it is necessary to form appropriate control loops. Due to the droop control, this can be most easily and efficiently done by splitting VSM model into two independent units, one related to active power and other to reactive power regulation. Based on these units, control loops for active and reactive power are formed, shown in Figs 2 and 3, respectively. During their formation, certain assumptions were adopted in order to achieve linearization and complete independence between the loops, and thus simplify the calculation of VSM parameters. This refers to the use of indicated values for the grid voltage and angular frequency of VSM instead of their actual values. Also, fixed value of electromotive force in the regulation of active power and fixed load angle in regulation of reactive power is used. Second member in expressions for electromotive force (5)-(7), is neglected.

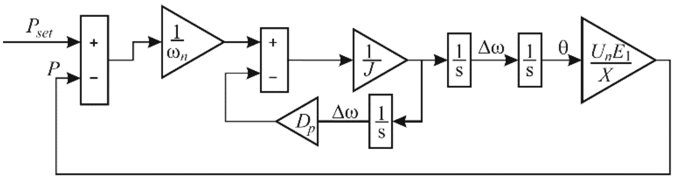

Fig. 2. Active power control loop

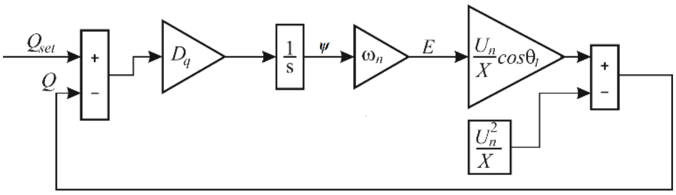

Fig. 3. Rective power control loop

Linearization was also achieved by replacing the sinusoidal function with its argument in expression for active power (13) and using fixed value for cosine function in expression for reactive power (14). These assumptions are justified if deviations of grid operating voltage and VSM frequency from their indicated values are small and if load angle does not take big changes. Also, product of flux and angular frequency of VSM has to be an order of magnitude greater than the change of VSM flux. All of this, to a large extent, should be met if values for active and reactive power are set in normal operating mode. Biger errors can occur by using inadequate fixed values for electromotive force and load angle of VSM in control loops. In order to partially overcome this, mentioned quantities were calculated on the basis of set values for active and reactive power.

In this paper, VSM emulates the operation of synchronous machine without losses and with cylindrical rotor, which active and reactive power can be determined by expressions:

$$P = \frac{U \cdot E}{X} sin\theta \tag{13}$$

$$Q = \frac{U \cdot E}{X} cos\theta - \frac{U^2}{X} \tag{14}$$

Where: P −active power that VSM injects into the grid, Q −reactive power that VSM injects into the grid, U −grid voltage, E −electromotive force of VSM, θ −load angle, X −equivalent reactance between electromotive force and voltage.

Taking into account mentioned assumptions while forming control loops for active and reactive power, (13) and (14) become:

$$P = \frac{U_n \cdot E_1}{X} \theta \tag{15}$$

$$Q = \frac{U_n \cdot E}{X} cos\theta_1 - \frac{U_n^2}{X} \tag{16}$$

Where E_1 and θ_1 are fixed values for electromotive force and load ange, determined by set values of active and reactive power, using expressions:

$$E_1 = \frac{\frac{Q_{seti}+Q_{seti-1}}{2} \cdot X + U_n^2}{U_n} \tag{17}$$

$$\theta_1 = sin^{-1}\left(\frac{\frac{P_{seti}+P_{seti-1}}{2} \cdot X}{U_n \cdot E_1}\right) \tag{18}$$

Where indices i and $i-1$ in active and reactive power references mark current and previous reference, respectively.

Equivalent reactance between electromotive force of VSM and grid voltage, which appears in expressions for active and reactive power, is the equivalent reactance of LCL filter, and can be found as:

$$X = X_1 - \frac{X_2 \cdot X_C}{X_2 - X_C} \tag{19}$$

Where: X_1 −reactance of the inductance near the VSM ($X_1 = \omega L_1$), X_2 −reactance of the inductance near the grid ($X_2 = \omega L_2$), X_C −reactance of the capacitor ($X_C = 1/C\omega$). Delay due to the change of currents in the network branches is neglected in control loops, because it is much less than what is needed to change flux or frequency and practically does not affect the dinamics of the system. Based on the control loop for active power, transfer function between the set and actual active power injected into the grid by VSM, can be found as:

$$\frac{P}{P_{set}} = F_p(s) = \frac{\frac{U_n E_1}{X\omega_n J}}{S^2 + \frac{D_p}{J}S + \frac{U_n E_1}{X\omega_n J}} \tag{20}$$

In this paper, pole adjustment method is used, which means that VSM parameters are calculated from desired values of characteristic parameters that determine the response of second order circuit. General expression for second order transfer function is:

$$F_s(s) = \frac{\omega_c^2}{s^2 + 2\xi\omega_C s + \omega_C^2} \tag{21}$$

Where ω_C is the natural frequency (bandwidth of second order circuit) and ξ is the damping factor of second order circuit. Comparing (20) and (21), moment of inertia and damping factor of VSM can be determined based on the desired damping factor and bandwidth of second order circuit:

$$J = \frac{U_n \cdot E_1}{X \cdot \omega_n \cdot \omega_C^2} \tag{22}$$

$$D_p = 2 \cdot \xi \cdot \omega_c \cdot J \tag{23}$$

Same analogy can be used for reactive power control loop, whose transfer function is given by expression:

$$\frac{Q}{Q_{set}} = F_q(s) = \frac{1}{1+\frac{X}{D_q \omega_n U_n cos\theta_1}s} \tag{24}$$

General form of the first order transfer function is:

$$F_s(s) = \frac{1}{1+sT} \tag{25}$$

Where T is the time constant of the first order circuit. Based on the desired value of time constant, ratio coefficient D_q can be found as:

$$D_q = \frac{X}{T \cdot \omega_n \cdot U_n \cdot cos\theta_1} \tag{26}$$

Now, values are determined for all required parameters of grid-feeding model of VSM. Values for an additional two parameters in grid-supporting model of VSM are determined based on the desired error between set and actual values of injected powers, during the deviation of grid voltage and frequency from the reference values, in steady state. This is shown in (27) and (28):

$$K_V = -\frac{P-P_{ref}}{V-V_{ref}} \tag{27}$$

$$K_\omega = \frac{Q-Q_{ref}}{\omega-\omega_{ref}} \tag{28}$$

Expressions (27) and (28) are obtain using (11) and (12) for steady state. Determined in this way, control coefficients have positive values. It must be taken into account that (27) and (28) are valid only in active resistance dominant grids, like one used in this paper.

IV. PRESENTATION AND ANALYSIS OF RESULTS

In this section, results related to the response of active and reactive power of VSM for different values of its parameters are presented and analyzed. Used active and reactive power references and the rating of VSM (40kVA) are such that they do not cause major voltage deviations in the formed low voltage grid model. All results were obtained for the case where VSM, powered by storage system DC voltage, is connected to the low voltage grid, modeled by real voltage generator, via LCL filter. This is shown in the form of Matlab/Simulink block in Fig. 4. For the *50 Hz* frequency grid resistance and grid reactance used in the model are: $R_g=0.1126\Omega$ and $X_g=0.0233\Omega$. Voltage generator in grid modeling is fixed 400V, 50Hz voltage source. Reactances of LCL filter are: $X_1=0.6283\Omega$, $X_2=0.1571\Omega$ and capacitor reactance $X_C=27.6791\Omega$ (equivalent reactance is $X=0.785\Omega$).

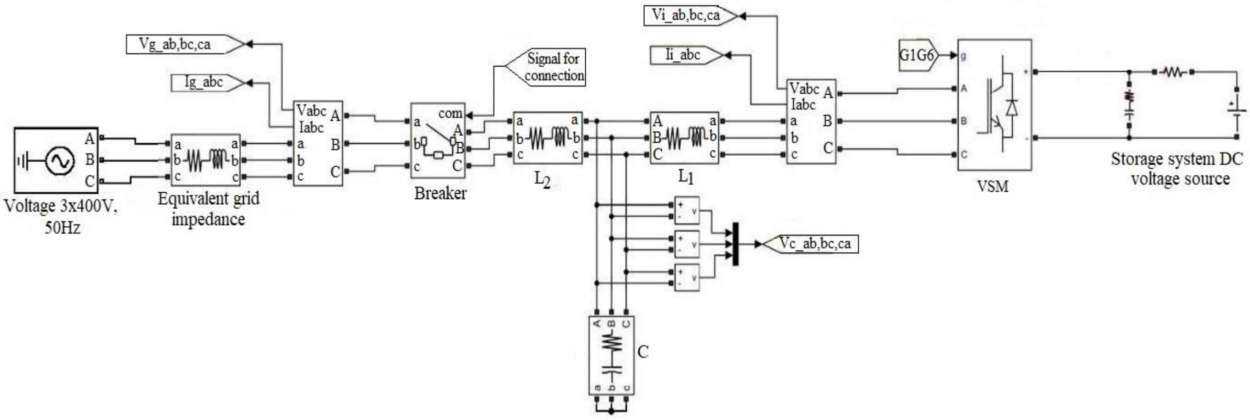

Fig. 4. Block model of power grid to which VSM, powered by storage system DC voltage, is connected via LCL filter

Next six figures show how efficient is the response of active and reactive power of grid-feeding model of VSM and to what extent it matches the desired (expected) responses. Desired response of active and reactive power is determined by chosen values of characteristic parameters ω_C, ξ and *T*. Based on those three characteristic parameters, using presented methodology, necessary values of parameters in grid-feeding model of VSM are determined, for three different cases, shown in Table I.

TABLE I
CHARACTERISTIC PARAMETERS OF THE DESIRED RESPONSE AND CALCULATED PARAMETERS FOR GRID-FEEDING MODEL OF VSM

Case	Natural frequency ω_C (rad/s)	Damping factor ξ	Time constant *T* (s)
1	10	0.707	0.15
2	7	1	0.15
3	14	0.5	0.2
Case	Moment of inertia *J* (kgm^2)	Damping coefficient $D_p(Nms/rad)$	Ratio coefficient $D_q(Wb/sVAr)$
1	6.4458	91.1441	$4.247 \cdot 10^{-5}$
2	13.1548	184.1667	$4.2454 \cdot 10^{-5}$
3	3.2887	46.0417	$3.184 \cdot 10^{-5}$

Figs 5 and 6 show reference, desired and actual response of active and reactive power for the case 1.

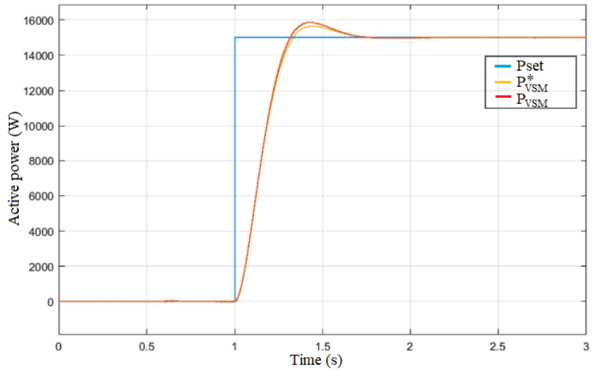

Fig. 5. Reference, desired and actual response of active power in grid-feeding model, case 1

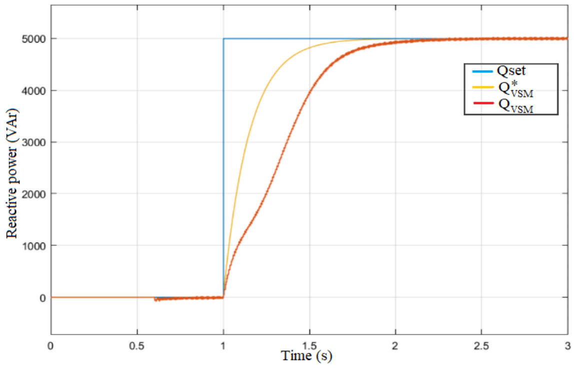

Fig. 6. Reference, desired and actual response of reactive power in grid-feeding model, case 1

Figs 7 and 8 show reference, desired and actual response of active and reactive power for the case 2.

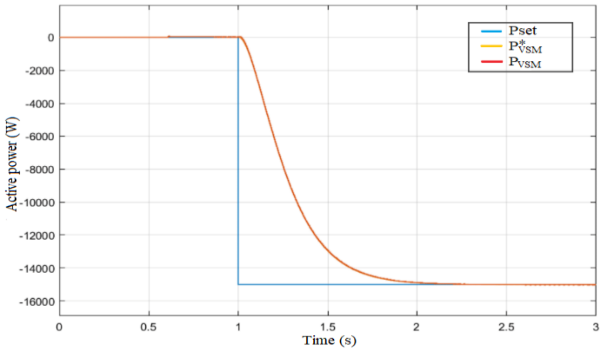

Fig. 7. Reference, desired and actual response of active power in grid-feeding model, case 2

Based on the Figs (5)-(10) it can be concluded that VSM operates efficiently and achieves desired references of active and reactive powers (positive or negative) with high precision. Also, great match between desired (expected) and actual active power response can be seen. In the case of reactive power, matching is not so great when active and reactive power have the same direction, in other cases it is quite good considering the simplicity of the methodology. This can be explained by the fact that voltage and frequency variations, have more affect on the dynamics of reactive than on the active power response, considering (20) and (24). Also, voltage variations are the largest when both powers have the same direction, that is way the worst matching is in the fig. 6.

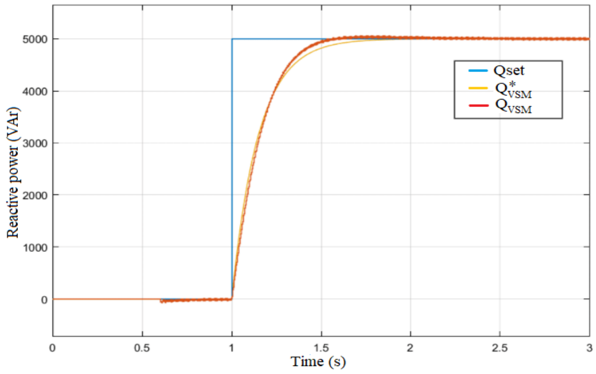

Fig. 8. Reference, desired and actual response of reactive power in grid-feeding model, case 2

Figs 9 and 10 show reference, desired and actual response of active and reactive power for the case 3.

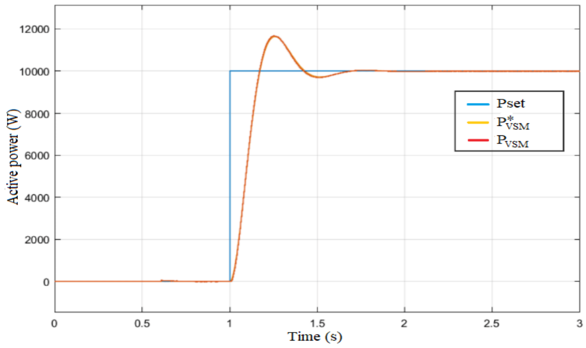

Fig. 9. Reference, desired and actual response of active power in grid-feeding model, case 3

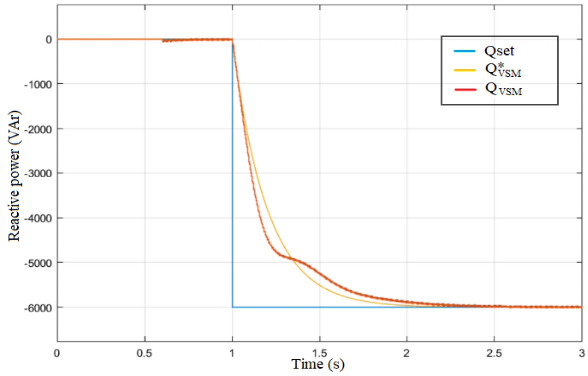

Fig. 10. Reference, desired and actual response of reactive power in grid-feeding model, case 3

In the grid-supporting model, references and actual values of injected powers will not match when there is a deviation in values of grid voltage and frequency compared to their referent values. This is shown in Fig. 11 for reactive and in Fig. 12 for active power.

TABLE II
CHARACTERISTIC PARAMETERS OF THE DESIRED RESPONSE AND CALCULATED PARAMETERS FOR GRID-SUPPORTING MODEL OF VSM

Natural frequency ω_C (rad/s)	Damping factor ξ	Time constant T (s)	Control coefficient $K_V(W/V)$
10	0.707	0.15	10 000
Control coefficient $K_\omega(VArs/rad)$	Moment of inertia $J\,(kgm^2)$	Damping coefficient $D_p(Nms/rad)$	Ratio coefficient $D_q(Wb/sVAr)$
30 000	6.3663	90.0189	$4.24\cdot 10^{-5}$

Table II contains values of characteristic parameters of the desired response, based on which values of parameters in grid-supporting model of VSM are calculated and also shown in Table II. Figs 11 and 12, are obtained for the case where parameters of grid-supporting model of VSM have values from Table II, and where grid voltage and frequency are below their referent values. High values for control coefficients are used due to fixed voltage source and low network impedance, which do not allow more significant changes in grid voltage and especially in grid angular frequency. There is a noticeable difference in both active and reactive power response shown in Figs 11 and 12, compared with those in Figs 5 and 6, which had the same values for characteristic parameters. This changed dynamics in grid-supporting model is the result of grid voltage and angular frequency errors used as inputs in active and reactive power control loops in which they are not considered in the first place. This means that presented methodology should be primarily used in grid-feeding model of VSM.

Considering the results for grid-feeding VSM model, it can be concluded that grid parameters have negative effect on active and reactive power response and decrease the accuracy of the proposed methodology by changing the voltage and frequency in the point of connection. This also applies to the grid-supporting model of VSM, but in that case voltage and frequency variations, caused by the grid impedance, in addition, enhance voltage and frequency support in the point of connection. Resistive or reactive nature of grid impedance determined which type of power should be used for voltage, and which for frequency support.

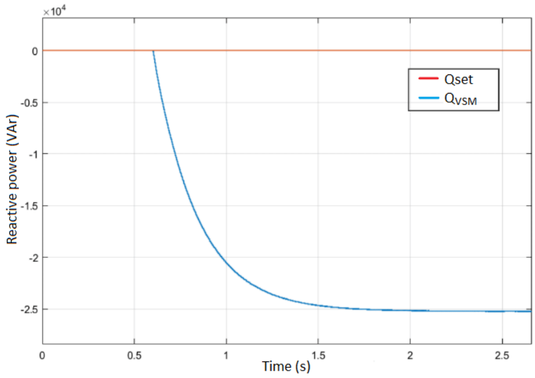

Fig. 11. Referent and actual value of reactive power in grid-supporting model

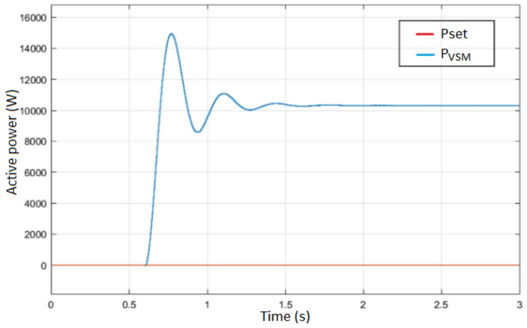

Fig. 12. Referent and actual value of active power in grid-supporting model

V. CONCLUSION

In this paper, model of VSM was made and methodology for determining the values of its parameters is presented and described in detail. Obtained results have shown that VSM is able to efficiently and accurately respond to different requirements of active and reactive powers. Proposed methodology for determining VSM parameter values is simple, and based on obtained results, quite accurate in achieving the desired response, if grid voltage and frequency deviations, due to power injection, are relatively small. Also, results have shown that if more precision in achieving the desired response is needed, proposed methodology should be primarily used in grid-feeding model of VSM. Taking into account the simplicity and efficiency of the presented methodology, its major practical value in real, more complex systems, could be reflected in determining the initial, first step, values of VSM parameters in order to achieve the desired response, which could then be corrected by additional steps, considering the characteristics of a particular system.

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