Pakistan Journal of Engineering and Technology, PakJET
Multidisciplinary | Peer Reviewed | Open Access
Volume: 03, Number: 03, Pages: 89 - 93, Year: 2020

An Extended Model Predictive-Sliding Mode Control for Three-Level AC/DC Power Converters

Muhammad Jamshed Abbass[1,*], Sohail Khalid[1], Muhammad Abdul Rahman[1], Muhammad Awais[2], Ali Waqar[2], and Faisal Saleem[1]

[1]Department of Electrical Engineering, Riphah International University, Islamabad, Pakistan
[2]School of Electrical and Electronics Engineering, North China Electric Power University, Beijing 102206, China

*Corresponding author: Muhammad Jamshed Abbas (Email: jamshed.abbass@riphah.edu.pk)

***Abstract*- An extended model predictive sliding mode controller (EMPSMC) is implemented for controlling AC/DC power converters (3-levels), which shows better performance. It is the trend to exploit the traditional proportional integration (PI) controller for the generation of active power reference, which gives the overshoot and steady state error. To overcome such errors, sliding mode control (SMC) is exploited. A comparison of performance of EMPSMC and MPPIC is presented in the paper. The introduction of SMC reduces the time lag of the system and reduces overshoot as is seen in the results. The simulation results validate the performance of the designed model.**

***Index Terms*-- Extended model-predictive control, Sliding-model control, Power converter, Model Predictive PI controller**

I. INTRODUCTION

A three-phase AC/DC Power converter has recently attained significant attention [1]. The power converter has versatile capabilities and usages, for example, controllable power factor, power flow direction control, line current harmonic minimization, and better voltage regulation. Hence, it is used in a wide range of areas like renewable generation resources (photovoltaic, wind, and biomass) [2], microgrid technology [3], railway electrification systems [4], and high voltage DC systems [5]. Various control techniques have been researched and applied to effectively and efficiently control power converters, e.g., model predictive control (MPC), a direct power control (DPC), and voltage-oriented control (VOC). The VOC has outstanding steady-state tracking capability and firm energetic response. The traditional VOC contained a dual looped construction, the external loop acts as a voltage control system, and the inward loop acts as a current control system. However, the existing loop and proportional-integral (PI) limitations are significantly dependent on the converter's dynamic performance[1, 6]. Currently, MPC based techniques have been proposed for power converters to improve system performance [7]. There are several benefits of the MPC technique as compared to the traditional controllers; for example, it optimizes the current state while considering future conditions [8], good tracking and steady-state stability, modulation free, can be easily fit into the algorithm, and have a faster response against disturbances and doubts.

Similarly, during the simulation process, the PI controller parameters remain fixed, limiting its dynamic performance, particularly during disturbances and uncertain circumstances. In the case of MPPIC, to satisfy the system's requirement, it is hard to discover a single conventional PI device parameters as long as the system changes its states; this is mainly due to its limitation of constant stimulation parameters. Another controller, the S.M.C. (sliding mode controller), exhibits excellent dynamic performance.

Moreover, SMC also has an extraordinary ability to discard uncertainties and disturbances like disparities in system parameters and control variables [9, 10]. The proposed approach is based on an extended MPSMC. The shortcomings of the conventional PI controller with MPPIC are tackled by replacing it with the SMC. Firstly, the necessary AC/DC power converter, MPC, and SMC are analyzed theoretically for in-depth understanding. In the next step, sampling time, active and reactive power is computed using the predicted value of the grid current, which results in improved computational time. We designed a control law and sliding surface for dc-voltage regulation of the power converter's active and reactive power by considering this feature.

Finally, the simulation is carried out to witness a dynamic presentation that will be obtained from the proposed scheme. A basic MPSMC based system model is shown in fig.1. The pulse-width-modulation (PWM) technique is used in the rotational frame (do coordinate) of the power converter's model to regulate the active and reactive power asymptotically. The classical VOC method is used to track its position [11]. The harmonics created by the PWM techniques are mostly at the Power-converter's output side; however, input current and power ripples can also be introduced [12], [13].

Another two loops, i.e., inner current, and outer voltage are also considered, ith PI controllers due to their simple anatomy. This paper's fundamental objective is to form a hybrid control technique by combining SMC and EMPC (EMPSMC) to counterbalance the traditional PI-based M.P.C. systems' drawbacks. The EMPSMC technique is also adopted to better track an active power position and enhance the following characteristics: Dynamic presentation of the system, Elevated overshoot, or undershoot issue.

II. SYSTEM DESCRIPTION AND ANALYTICAL MODELING

The circuitory of a AC/DC (3-level) power converter comprises of 6 MOSFET switches shown in Fig.1.

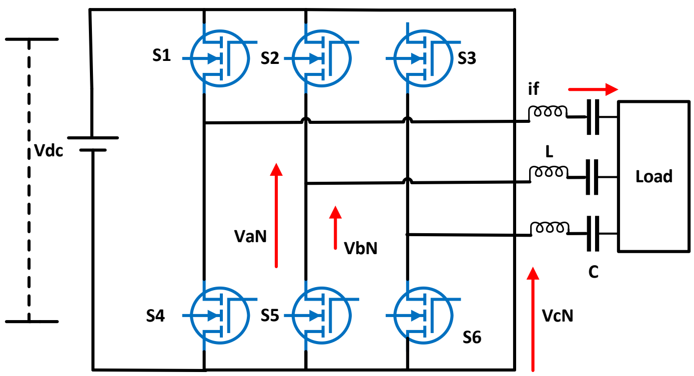

FIGURE 1: Circuitory of a AC/DC (3-level) power converter.

The three-phase system is connected with these switches though RL filters have the same resistance and inductance values. The output voltage harmonics on the Dc side are filtered using a capacitor filter C. Equation 1 represents the three-phase power converter's mathematical model. V_{ga}, V_{gb}, and V_{gc} and three-phase input voltages and i_{ga}, i_{gb}, and i_{gc} are respected currents of phases a, b and c. The converter input voltages are V_{ca}, V_{cb}, and V_{cc}; Vdc is the output voltage across load resistor RL and iL is the corresponding load current. Where S_k is the switching state of each phase k. For instance, if S_a=1;

$$S_k = \begin{Bmatrix} 1, upperSwitchON \\ 0, upperSwitchOFF \end{Bmatrix} \qquad (1)$$

Based on Clarke transformation, three-phase switching states can be transformed into two phases $\alpha\beta$ as;

$$S_{\alpha\beta} = \begin{bmatrix} S_\alpha \\ S_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} * \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} \qquad (2)$$

where $S_{\alpha\beta}$ is the switching matrix. Based on this matrix, the two-phase input voltage can be represented on the three-phase input voltage and described on the two phases αβ in the form of eight vectors by using space vector pulse width modulation (SVPWM) scheme, as shown in Fig.2.

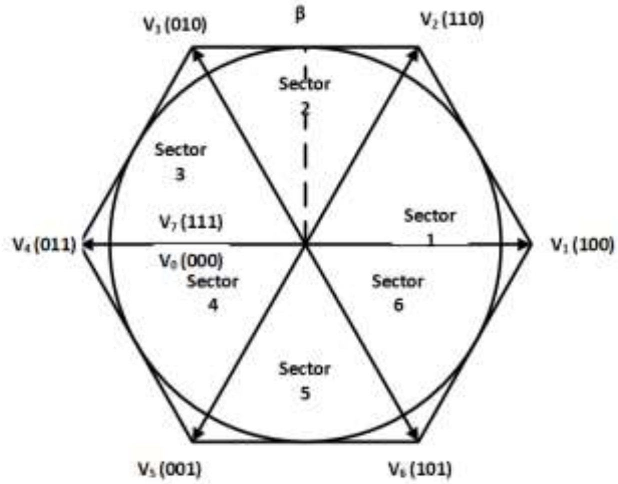

FIGURE 2: Voltage vectors representation using the Clarke transformation (αβ coordinate system) the two voltage vectors V0 and V7 are zero, respectively.

Based on this representation, the two-phase model can be represented as follows;

$$\boldsymbol{V}_{g,\alpha\beta} = \boldsymbol{L}^{\circ}_{\alpha\beta} + R\boldsymbol{i}_{\alpha\beta} + \boldsymbol{V}_{\alpha\beta} \qquad (3)$$

III. CONTROL STRATEGY

In the MPPIC controller-based approach, the traditional PI controller is implemented to uphold the output voltage reference. However, the PI controller's limitation is that it has fixed parameters set, and the system's dynamic performance becomes undesirable and slow when the system's demand or parameters are variable. To resolve this limitation, SMC, which has prominently better steady-state stability and dynamic performance than PI, is adopted in the proposed approach, as shown in Fig 3.

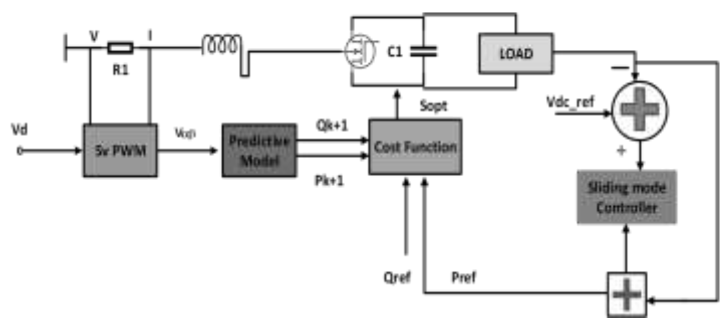

FIGURE 3: The system Block diagram of the EMPSMC scheme

The discrete-time model of power converter at the (n+1)th sample is given by;

$$\begin{cases} i_{g\alpha}(n+1)^{\bullet} = T_s(-\frac{R}{L}i_{g\alpha}(n) + \frac{1}{L}V_{g\alpha}(n) - \frac{1}{L}V_\alpha(n)) \\ i_{g\beta}(n+1)^{\bullet} = T_s(-\frac{R}{L}i_{g\beta}(n) + \frac{1}{L}V_{g\beta}(n) - \frac{1}{L}V_\beta(n)) \end{cases} \qquad (4)$$

where Ts is the sampling time, then the active (P) and reactive (Q) powers of the system are:

$$\vartheta = \sqrt{(P - P_{ref})^2 + (Q - Q_{ref})^2} \qquad (5)$$

$$Q_{ref} = 0$$

The Q_{ref} and Pref are the references of active and reactive power, and the function ϑ is used to find the optimal space vector for the upcoming switching step with a minimal value of cost function. The primary control problem is to derive a proper control law to track the desired dc voltage level. The instantaneous power can be expressed in terms of dc voltage as;

$$P_{dc} = P_i = C * V_{dc} * \frac{d}{dt} V_{dc\frac{1}{RL}} * V_{dc}{}^2 \qquad (6)$$

The output and instantaneous power of the converter becomes equal at equilibrium. Moreover, under steady-state conditions, the immediate and active power becomes equal; however, it can be seen from eq (6) that it is directly proportional to dc voltage. So, for controlling the active power, the SMC is exploited to manage dc voltage. This urges the need for an appropriate control law from which the desired dc voltage Vdc_ref value can be accurately obtained from the control variable Vdc. Equation (7) represents the tracking error.

$$e_v = V_{dc} - V_{dc_{ref}} \qquad (7)$$

The SMC controller, modeling the sliding surface, is a significant step toward achieving the desired control law. The sliding surface design can be obtained from the error and derivative of the error. The position vectors are required to reach and slide on this surface to minimize the error, as shown in Fig.5, where λ is the excellent time constant.

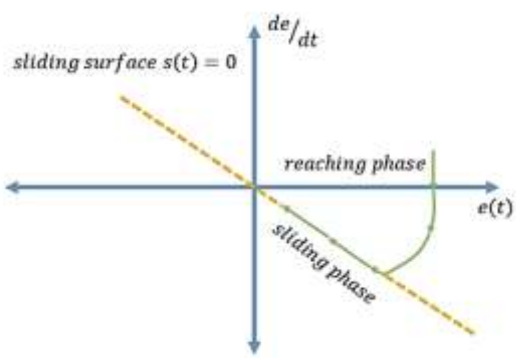

FIGURE 4: Trajectory Plot like any sliding action into SMC

Based on the sliding surface model, the control law U in terms of instantaneous power can be expressed as;

$$U = \begin{Bmatrix} P_{dc}{}^{+}, S_v > 0 \\ P_{dc}{}^{-}, S_v < 0 \end{Bmatrix} \qquad (8)$$

From the above analysis, controller design is expressed as;

$$u_{sv} = P_{ref} = C * V_{dc} \begin{bmatrix} \left(\frac{1}{R_L * C} - \frac{1}{\lambda}\right) V_{dc} + \frac{1}{\lambda} V_{dc_{ref}} \\ -(\rho + k) sign(S_v) \end{bmatrix} \qquad (9)$$

where ρ bound on the uncertainty of disturbance, k controller gain, and $sign(.)$ the sigmoid function.

IV. RESULTS AND DISCUSSION

In this section, the tracking performance of the proposed scheme is evaluated. Moreover, the output response is also compared with the MPPIC method to track performance without disturbance.

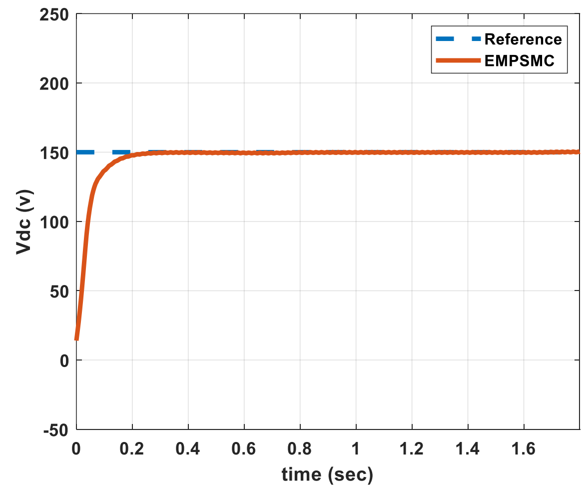

FIGURE 5: The output response of Step Response of EMPSMC schemes

Figure 5 shows the steady-state response of the dc-link voltage; Vdc is the output on the Dc side of the power converter. The dynamic response of the EMPSMC is also much better and fast than the convention MPPIC technique, as can be seen in Table I.

Table I: Dynamic Performance Evaluation of EMPSMC and MMPIC

Controller Characteristics		Comparison of Table		
	EMPSMC	**[14]-[15]**	**MPPIC**	**[14]-[15]**
Rise Time	**0.0873 Sec**	**0.125 sec**	**0.1327 sec**	**--**
Overshoot	**0.1886%**	**2.33%**	**0.8776%**	**2.65%**

The EMPSMC model's performance is further compared with the already developed model for three-phase Ac/Dc power Converter, presented in [14-15]. In [14], a robust MPSMC controller is presented, tracking performance for the step input is very good. To evaluate the proposed model's performance, a measured disturbance of 10V is added to the system from t=0.4 sec to 0.43 sec. The proposed controller's response is speedy, and the output reference rapidly attains the actual position. Overall, the EMPSMC based system's performance is very smooth and responsive with a rise time of 0.1087 seconds, and the undershoot of the system is 1.0967%. Figure 8 shows the disturbance rejection capability of the system.

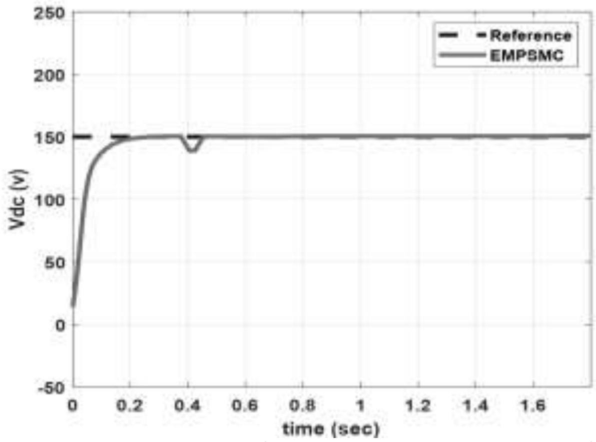

FIGURE 6: The Output response of the system with EMPSMC plus interference (Disturbance)

It can be observed that the output response shows a little deviation due to the added disturbance. However, to further justify the proposed system's superiority, its tracking performance is compared with the MPPIC based system. To validate the proposed controller's real-time performance capabilities, the end-users load demand first increased and decreased during the simulation process. Figure 6 shows the response of the proposed approach to an unpredicted rise in the load. At t=1 sec demand is stepped up from 150 to 200 V. The proposed EMPSMC took 0.0401 sec to match new load demand with very little error.

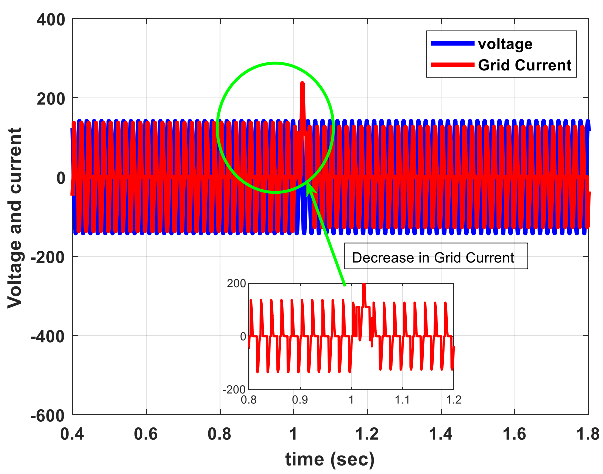

FIGURE 7: Output reaction to an unpredicted of dc voltage load demand increase Phase A voltage and current decreases under EMPSMC

Moreover, EMPSMC forces the dc voltage value to the new desired reference with almost very low/less overshoot. Figure 7 shows that the active power dynamic response is much faster and reaches the steady-state value of 300 W. Figure 8 shows the step response performance of the EMPSMC, MPPIC, and MPC. MPPIC responds to the reference slowly. On the contrary to this, EMPSMC responds quickly and settles down in a short time. EMPSMC performance is way better than the conventional MPC and MPPIC for tracking the reference.

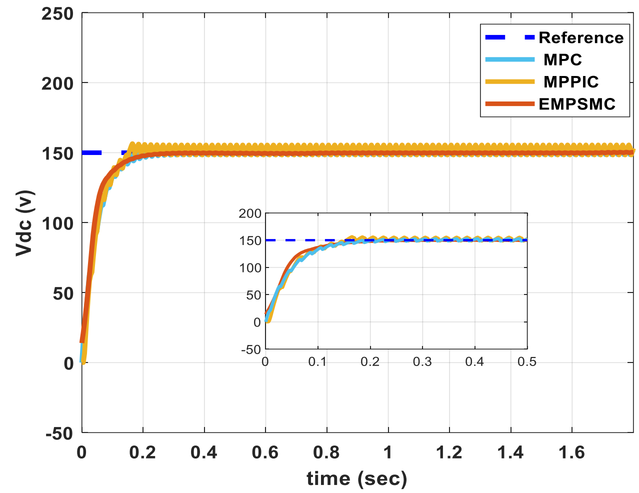

FIGURE 8: Comparison of EMPC, MPPIC, and MPC

V. CONCLUSION

The designed model is validated for tracking the active power reference. Moreover, a measured disturbance is added to simulate a more rigorous analysis. The results with and without disturbance are auspicious, and the reference signal was tracked accurately. In the next stage, EMPSMC is used to supply a real-time varying load demand. The tracking of the proposed scheme was adaptive, and results showed that with the variation of demand, the proposed scheme promptly responds and adjusts the output by the change in demand. Moreover, there is no steady-state error and significantly less over/undershoots. For the proposed scheme, the grid current and active power response are also exact and fast. The simulation model is also validated for the previous MPC and MPPIC and analyzed. The proposed EMPSMC only took 0.1088sec to be stable at the required voltage, while the conventional method took double time. The overshoot of EMPSMC was 0.1886 %, MPPIC was 0.8776 %, and the MPC 0.6819%. The proposed scheme is vigorous, efficient, and adaptive compared to the MPPIC under different operational conditions.

REFERENCES

[1] Y. Zhang, "Model predictive direct power control of a PWM rectifier with duty cycle optimization," IEEE Trans. Power Electron., vol. 28, no. 11, pp. 5343-5351, Nov. 2013.

[2] H. Liu, "Contribution of VSC-HVDC to Frequency Regulation of Power Systems With Offshore Wind Generation," IEEE Trans. Energy Convers., vol. 30, no. 3, pp. 918-926, Sep. 2015.

[3] M. Davari, "Robust multi-objective control of VSC-based dcvoltage power port in hybrid ac/dc multi-terminal microgrids," IEEE Trans. Smart Grid, vol. 4, no. 3, pp. 1597-1612, Mar. 2013.

[4] G. Antonio, "VSC-Based MVDC railway electrification system," IEEE Trans. Power Del., vol. 29, no. 1, pp. 422-431, Jan. 2014.
[5] G. Venkataramanan, "A superconducting DC transmission system based on VSC transmission technologies," IEEE Trans. Appl. Supercond., vol. 13, no. 2, pp. 1922-1925, Feb. 2003.
[6] R. Kadri, "An improved maximum power point tracking for photovoltaic grid-connected inverter based on voltageoriented control," IEEE Trans. Ind. Electron., vol. 58, no. 1, pp. 66-75, Jan. 2011.
[7] C. Bordons, "Basic Principles of MPC for Power Converters: Bridging the Gap Between Theory and Practice," IEEE Industrial Electronics Magazine, vol. 9, no. 3, pp. 31-43, Sep. 2015.
[8] S. Kwak, "Model-Predictive Direct Power Control with Vector Preselection Technique for Highly Efficient Active Rectifiers," IEEE Transactions on Industrial Informatics, vol. 11, no. 1, pp. 44-52, Sep. 2015.
[9] J. Lee, "DSP-based sliding-mode control for electromagnetic levitation precise-position system." IEEE Transactions on Industrial Informatics, vol. 9, no. 2, pp. 817-827, Sep. 2015.
[10] S. Li, "Design and Implementation of Clutch Control for Automotive Transmissions Using Terminal Sliding-Mode Control and Uncertainty Observer," IEEE Transactions on Vehicular Technology, vol. 65, no. 4, pp. 1890-1898, April 2016.
[11] R. Kadri, J. P. Gaubert, and G. Champenois, "An improved maximum power point tracking for photovoltaic gridconnected inverter based on voltage-oriented control," IEEE Trans. Ind. Electron., vol. 58, no. 1, pp. 66–75, Jan. 2011.
[12] W. Shireen, R. A. Kulkarni, and M. Arefeen, "Analysis and minimization of input ripple current in PWM inverters for designing reliable fuel cell power systems," J. Power Sources, vol. 156, no. 2, pp. 448–454, Jun. 2006.
[13] J. Dannehl, C. Wessels, and F. W. Fuchs, "Limitations of voltage-oriented PI current control of grid-connected PWM rectifiers with LCL filters," IEEE Trans. Ind. Electron., vol. 56, no. 2, pp. 380–388, Feb. 2009.
[14] J. J. More, P. F. Puleston, and C. Kunusch, "Development and implementation of a supervisor strategy and sliding mode control setup for fuel-cell-based hybrid generation systems," IEEE Trans. Energy Convers., vol. 30, no. 1, pp. 218–225, Mar. 2015.
[15] X. Zhang, L. Sun, and K. Zhao, "Nonlinear speed control for PMSM system using sliding-mode control and disturbance compensation techniques," IEEE Trans. Power Electron., vol. 28, no. 3, pp. 1358–1365, Mar. 2013.