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IMPROVED STEADY STATE AND LARGE SIGNAL TRANSIENT RESPONSE OF THREE LEVEL AC-DC CONVERTER USING HYSTERESIS MODULATION BASED SMC UNDER DCM

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Keywords: Three level full bridge ac-dc converter, Hysteresis modulation-based sliding mode controller (HMSMC), Discontinuous conduction mode (DCM), Line and load variations.

Abstract: This paper presents a Hysteresis Modulation based Sliding Mode Controller (HMSMC), for single stage three level full bridge ac-dc converter under discontinuous conduction mode (DCM). Compared with the conventional methods like PI, fuzzy and sliding mode controller, this HMSMC is capable of attaining the improved steady state and large signal transient response under variations occur at supply and load side. State space averaging method is used here to derive the dynamic equations of the converter. Also, using the theory of hysteresis modulation for wide operating region derives the switching frequency of the converter. The Simulink model of the presented PFC ac-dc converter with HMSMC circuit is verified with Matlab/Simulink. The HMSMC for the converter is analyzed for line variations, load variations and for non-linear component variations.

1. INTRODUCTION

It has been established in recent years that electrical energy conversion can be done by using ac-dc converters for numerous applications like PCs, telecommunication power supplies, battery chargers, etc. [1, 2]. Conversion of electrical energy has been done in two conversion stages in ac-dc converter: the first one is power factor correction stage and the second one is dc-dc regulation stage. These two stages are used to ensure the power quality improvement in the line side within the standard value [3,4].

Active power factor correction technique has two methods: One is two-stage power factor correction method and the other one is single stage power factor correction (SSPFC) method. In two stage power factor correction converters, electrical energy conversion can be done using two converter stages, namely one stage for an ac-dc rectification and the other one for dc-dc conversion with passive elements. But in SSPFC method, both conversions can be carried out in one converter itself without the need of any extra switches and passive elements. SSPFC converters with discontinuous mode of operation are widely used for low power application due to excessive voltage that appears across the converter switches [5]. This voltage stress can be reduced using effective strategy which improves the steady and dynamic performance of the converter.

The converters always exhibit highly non-linear dynamic behavior due to variations occurring in the operating parameters and the switching nature of the converters. The design of better controller for the converters is a challenging task in the field of power electronics. Generally, an efficient control method for converter always assures the stability and better dynamic performance in wide operating range. Moreover, improved response needs to be achieved with the consideration of load changes, input voltage changes and converter non-linear parameter variations.

Generally, linear control methods are implemented on switch mode power converters to improve the system performance in the required operating range. If the required operating range is high, then the linear controller is not operating with better converter performance parameters and it leads to poor regulation of the converter due to the non-linearity. Due to these non-linearity, linear control methods are not efficient for wide operating range. To solve this issue, non-linear control methods are implemented. Non-linear control has the capability to control the system even under large signal dynamics and parameter variations where the linear controller fails. Sliding mode control (SMC) comes under the concept of non-linear control which is working for variable structure system and it is customarily appropriate to switch mode power converters with high level of difficulty. Even though, the sliding mode control method has many advantages compared with linear control methods like improved stability and reliability, robustness, better dynamic response even under large line and load variations. Various research studies have dealt with dc-dc converters with the concept of SMC with different types of sliding surfaces in several decades [6– 8]. Numerous works cited in the literature have been proposed to eliminate the common issues associated with sliding mode controller in switch mode power supplies. Reduction of output voltage error is attained for a three-level full bridge converter using PWM control based sliding mode controller [9]. Improved steady state and dynamic response is attained using HMSMC for Luo converter [10]. The state space averaging model has been derived to analyze the modeling strategies for switching converters. In this paper, HMSMC is applied for three level converter to address the instabilities due to line, load and component value variations. Steady and dynamic performance of the converter is evaluated using three different control techniques like PI, Fuzzy and Fuzzy tuned PI controllers at different loading conditions [11].

PWM based adaptive sliding mode controller is designed with suitable control equations for obtaining better converter performance parameters for dc-dc boost converters. In this paper, sliding co-efficient are derived from state space model of the converter with modes of operation of the converter [12]. High gain converter is evaluated with PI controller using obtaining small signal model for getting better performance of the converter [13].

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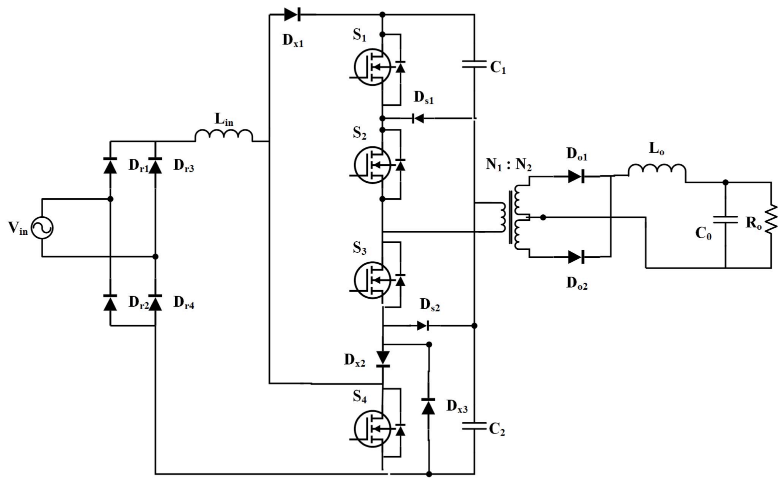

Fig. 1 – Single phase single stage three level full bridge ac-dc converter.

In section 1, the operation of the three-level full bridge ac-dc converter is explained in detail. In section 2, state space averaged model for the three-level full bridge ac-dc converter is derived to obtain the sliding mode controller. In section 3, the hysteresis modulation-based sliding mode controller is designed with variable switching frequency for controlling the switching pulses of the converter by limiting their band width which provides comparatively better steady state and dynamic responses than the linear controllers. Simulation is done with Matlab/Simulink. Operation of the converter, state space averaged analysis, control strategy and simulation results for the three-level full bridge ac-dc converter are presented in the subsequent sections.

Circuit diagram of presented converter is shown in Fig. 1. This converter is designed with two independent controllers which are used to improve converter performance in a single converter. First controller is ac–dc PFC section, which is used to perform the PFC converter by giving proper switching signals to S_4. Second controller is dc-dc three level full bridge section which is used to obtain the regulated output voltage by proper tuning of switching signals to all four switches. It should be noted that both the controllers are not dependent on each other because they can be implemented independently. In this paper, converter is analyzed with discontinuous conduction mode only. There is no reason behind why the converter is not analyzed with continuous current mode because DCM is desired phenomenon for the analysis.

2. STATE SPACE ANALYSIS FOR THREE LEVEL AC-DC CONVERTER TO DESIGN SMC UNDER DCM

In the design of the converter, the following assumptions are made: Converter has ideal semiconductor switches and ripple content is zero in the dc bus voltage.

2.1. STATE SPACE MODELING FOR PFC CONVERTER

State space averaged model is the primary focus to derive the modeling equations of the converter under discontinuous conduction mode. State space equations are derived from converter modes of operation. The non-conducting times (or) intervals between the switching states are neglected for the easy modeling procedure, because those intervals are very minimum intervals compared with three main intervals as shown in Fig. 2. By using these three main intervals, dynamic equations are derived for the presented converter. Therefore, the fundamental operation of the converter is explained with the following three cases to derive the state space equations:

For the modeling of the converter under DCM operation, the supply side inductor current (i_{Lin}), voltage across the capacitors C_1 and C_2 (V_{c1} & V_{c2}) are examined as state variables v_1, v_2 and v_3 to obtain converter state analysis.

Case 1: ($0 \le t \le d$*)*, S_1 and S_2 are in conduction state and S_4 turns on. Simultaneously, the rectified voltage V_{rec} is enforced across the input inductor in order that input inductor current increases. The dynamic equations for this part is given in equation (1)

$$\left.\begin{aligned} \frac{\mathrm{d}i_{Lin}}{\mathrm{d}t} &= \frac{V_{rec}}{L_{in}} = \dot{v}_1 \\ \frac{\mathrm{d}V_{c1}}{\mathrm{d}t} &= -\frac{i_p}{C_1} = \dot{v}_2 \\ \frac{\mathrm{d}V_{c2}}{\mathrm{d}t} &= 0 = \dot{v}_3 \end{aligned}\right\} \tag{1}$$

where, V_{rec} – rectifier output voltage, i_p – primary current of the transformer.

Case 2: ($0 \le t \le D-d$*)*, in this mode, dynamic equations are derived when switch S_3 is on and S_4 is off. This mode occurs when the input inductor discharges its energy. The dynamic equations for this part are given in equation (2),

$$\left.\begin{aligned} \frac{\mathrm{d}i_{Lin}}{\mathrm{d}t} &= \frac{V_{rec}}{L_{in}} - \frac{V_{c1}}{L_{in}} - \frac{V_{c2}}{L_{in}} = \dot{v}_1 \\ \frac{\mathrm{d}V_{c1}}{\mathrm{d}t} &= \frac{i_{Lin}}{C_1} - \frac{i_p}{C_1} = \dot{v}_2 \\ \frac{\mathrm{d}V_{c2}}{\mathrm{d}t} &= \frac{i_{Lin}}{C_2} = \dot{v}_3 \end{aligned}\right\} \tag{2}$$

Case.3 ($0 \le t \le 1-D-d$*):* Third set of dynamic equations is derived with zero inductor current. This mode occurs when all the switches are in off state. The dynamic equations are given in equation (3)

$$\left.\begin{aligned} \frac{\mathrm{d}i_{Lin}}{\mathrm{d}t} &= 0 = \dot{v}_1 \\ \frac{\mathrm{d}V_{c1}}{\mathrm{d}t} &= -\frac{i_p}{C_1} = \dot{v}_2 \\ \frac{\mathrm{d}V_{c2}}{\mathrm{d}t} &= 0 = \dot{v}_3 \end{aligned}\right\} \tag{3}$$

By using the above three cases, the converter overall state space equation is obtained with the following condition, time period for DCM operation = $(1–D–d)$

Equations (1) – (3) give the average model of the converter in the following form:

$$\dot{v} = Av + Bu + D$$

$$\begin{bmatrix} \dot{v}_1 \\ \dot{v}_2 \\ \dot{v}_3 \end{bmatrix} = \begin{vmatrix} 0 & \frac{1}{L_{in}} & \frac{1}{L_{in}} \\ -\frac{1}{C_1} & 0 & 0 \\ -\frac{1}{C_1} & 0 & 0 \end{vmatrix} \begin{vmatrix} i_{Lin} \\ V_{c1} \\ V_{c2} \end{vmatrix} + \begin{vmatrix} \frac{V_{c1}}{L_{in}} + \frac{V_{c2}}{L_{in}} \\ \frac{i_{Lin}}{C_1} - \frac{i_p}{C_1} \\ \frac{i_{Lin}}{C_2} \end{vmatrix} u + \begin{vmatrix} \frac{V_{rec}}{L_{in}} \\ 0 \\ 0 \end{vmatrix}$$

2.2. DCM OPERATION OF AC-DC CONVERTER

DCM operation of the converter is quite different from continuous conduction mode (CCM) operation based on conduction intervals. The converter with DCM operation has additional zero-inductor current stage compared with CCM operation. Due to this zero-inductor current stage, three-linear structure state trajectory S exists in the sliding plane as shown in Fig. 3.

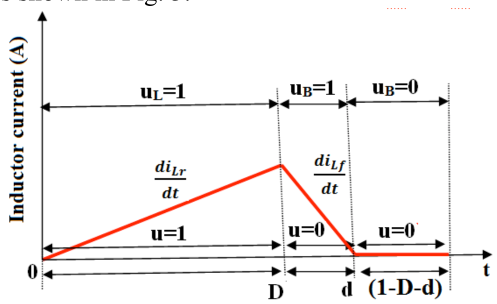

Fig. 2 – Input inductor current waveform under discontinuous conduction mode with assumption of virtual switching components

$\frac{\mathrm{d}\, i_{Lr}}{\mathrm{d}t}$ and $\frac{\mathrm{d}\, i_{Lf}}{\mathrm{d}t}$ indicates rate of change of inductor current during rising and falling.

Operation of the converter with DCM is considered here for the detailed analysis. The converter has tri-linear switching structure due to zero-inductor current, which is one of the additional switching states in the DCM compared with the CCM. So, the modeling of the converter with DCM is more difficult than CCM. To solve this issue, state space models of the converter with DCM are derived by proposing two technical parameters, known as the virtual switching elements (u_L and u_B), into the models as shown in Fig. 2. This is only valid for theoretical explanation. But, practically, no extra switch is required in the converter model to explain these virtual switching elements. In this converter state model, the virtual switching elements u_L and u_B can be represented with the actual status of the switch u. These virtual elements can be explained with numerical conditions 1 and 0 and it can be used to explain the ON and OFF statuses of the power switch. The above conditions are implemented in the actual model [14].

$$u_L = \begin{cases} 1 = ON\ when\ i_{Lin} > 0 \\ 0 = OFF\ when\ i_{Lin} = 0 \end{cases} \tag{4}$$

$$u_B = \begin{cases} 1 = ON\ when\ i_{Lin} > 0\ and\ u = 0 \\ 0 = OFF\ when\ i_{Lin} = 0\ and\ u = 0 \end{cases} \tag{5}$$

Here, equation (4) derives u_L to obtain numerical condition 1 while inductor current (i_{Lin}) increases from zero, and equation (5) derives u_B to obtain a numerical condition 1 only for discharging the input inductor current when the power switch is in the non-conduction state (u = 0).

2.3. DESIGN OF SLIDING MODE CONTROLLER USING SYSTEM MODELING EQUATIONS UNDER DCM OPERATION

SMC is a non-linear control method which is developed to improve the dynamic behavior of non-linear system in the variable structure field. SMC is the most required control technique for non- linear system because it has good stability and reliability, robustness and fast dynamic response against parameter variations, line and load variations. Moreover, SMC has flexible design choices and comparatively easier for implementing than the other non-linear controllers.

In the following section, the detailed modeling procedure for designing the SMC for three presented converters under DCM operation are provided.

To design HMSMC with DCM condition, express the state variables which are taken from the converter circuit.

$$\left.\begin{aligned} x_1 &= V_o - V_{ref} \\ x_2 &= V_{c1} - V_{c1ref} \\ x_3 &= V_{c2} - V_{c2ref} \end{aligned}\right\} \tag{6}$$

From eq. (6), derivative of state variables with respect to time gives the state-space representation which is needed to design the SM controller of the converter. State space description for the converter under DCM is given by:

$$\dot{x} = Ax + By + D,$$

where $y = u$ or $\bar{u}$ is the on and off conditions of the switches. In the following section, the conditions for sliding mode controller can be derived.

2.3.1. CONDITIONS FOR DESIGNING SMC

SMC has three fundamental mechanisms of the sliding mode process, namely hitting condition, existence condition, and stability condition.

State variables are expressed in eq. (6) to meet hitting condition of HMSMC,

Hitting condition- It guarantees that the state variables-controlled path of the converter system is always forced to the direction of sliding manifold (S) without considering initial status of the controller. Control law is given below which explains the hitting condition of SMC depending upon the state variables (x_1, x_2, and x_3),

$$\boldsymbol{u} = \begin{cases} \boldsymbol{1} \;\; \rightarrow \;\; \boldsymbol{u_B = 0}\ ;\ \boldsymbol{when}\ \ \boldsymbol{S > 0} \\ \boldsymbol{0} \;\; \rightarrow \;\; \boldsymbol{u_B = 1}\ ;\ \boldsymbol{when}\ \ \boldsymbol{S < 0} \\ \boldsymbol{0} \;\; \rightarrow \;\; \boldsymbol{u_B = 0}\ ;\ \boldsymbol{when}\ \ \boldsymbol{S < 0} \end{cases}$$

Based on the above control law, state variables of the converter are passing through sliding path of the sliding plane under discontinuous mode of operation and captured nearby suitable locations. Then the state space equation of the sliding plane is represented by a direct combination of state variables $x_{i\,(i=3)}$ and sliding coefficients

$$S = K_1 x_1 + K_2 x_2 + K_3 x_3,$$

where K_1, K_2, and K_3 are sliding coefficients; S – instantaneous state trajectory

Existence condition- This condition verifies that converter state variables are forced to stay back around the sliding plane by giving proper control to the converter switches under discontinuous operation mode. This ac-dc converter with DCM has a tri-linear structure trajectory as shown in Fig. 3. Structures 1 and 2 of the sliding path will give a sufficient condition to meet reaching phase for satisfying the existence condition. Third structure is diverging structure that will occur due to zero-inductor current. This diverging structure is not necessary to obtain the existence condition. Sliding path is controlled and directed to reach the fixed operating point without considering this diverging structure.

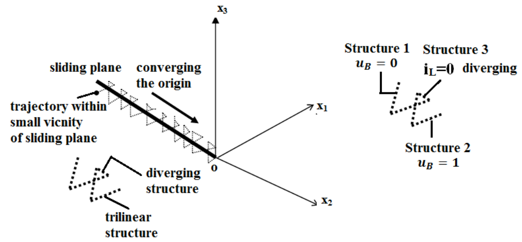

Fig. 3 – Tri-linear structure trajectory under DCM operation

The existence condition is given below [10]:

$$\lim_{S\to 0} S\dot{S} < 0,$$

$$\dot{S}_{S\to 0} = K^{\mathrm{T}}Ax + K^{\mathrm{T}}By_{S\to 0} > 0, \tag{7}$$

$$\dot{S}_{S\to 0} = K^{\mathrm{T}}Ax + K^{\mathrm{T}}By_{S\to 0} < 0, \tag{8}$$

$K^{\mathrm{T}} = [K_1\ K_2\ K_3]^{\mathrm{T}}$ – sliding co-efficient matrix; A – plant Matrix; B – input matrix; $y = u$ (status of the converter switch under CCM or DCM).

Due to this three-linear trajectory, existence condition for the sliding mode controller is explained with the following three cases based on the status of the power switches.

Case.1: $\dot{S} > 0$

Substitution of $y_{S\to 0} = u = 1$and $u_B = 0$ in equation (7) yields

$$\frac{K_1}{L_{in}}\left[V_{c1} + V_{c2} - V_{c1ref} - V_{c2ref}\right] - \frac{K_2}{C_1}\left[V_o - V_{ref}\right] - \frac{K_3}{C_2}\left[V_o - V_{ref}\right] + \frac{V_{rec}}{L_{in}} > 0 \tag{9}$$

Case.2: $\dot{S} < 0$

Substitution of $y_{S\to 0} = u = 0$ and $u_B = 1$ in equation (8) results in

$$\begin{aligned} &\frac{K_1}{L_{in}}\left[V_{c1} + V_{c2} - V_{c1ref} - V_{c2ref}\right] - \frac{K_2}{C_1}\left[V_o - V_{ref}\right] - \frac{K_3}{C_2}\left[V_o - V_{ref}\right] \\ &+ \frac{K_1}{L_{in}}\left[V_{c1} + V_{c2}\right] + \frac{K_2}{C_1}\left[i_{Lin} - i_p\right] + \frac{K_3}{C_2} i_{Lin} + \frac{V_{rec}}{L_{in}} < 0 \end{aligned} \tag{10}$$

Case.3: $\dot{S} < 0$

Substitute $y_{S\to 0} = u = 0$ and $u_B = 0$ in equation (8) gives

$$\frac{K_1}{L_{in}}\left[V_{c1} + V_{c2} - V_{c1ref} - V_{c2ref}\right] - \frac{K_2}{C_1}\left[V_o - V_{ref}\right] - \frac{K_3}{C_2}\left[V_o - V_{ref}\right] + \frac{V_{rec}}{L_{in}} < 0$$

By considering the above three cases, Existence condition has been derived for three sub-intervals. Only sub-intervals for Cases 1 and 2 are valid to achieve the existence condition for SMC so as to assure that the sliding path will stay back on a small area of the sliding plane. The existence condition is valid for eqs. (9) and (10) whenever those conditions are true.

3. DESIGNING OF HMSMC FOR THREE LEVEL FULL BRIDGE AC-DC CONVERTER

Figure 4 represents the sliding path for ideal SMC, which is forced to move exactly in the direction of the sliding plane without any high frequency oscillation at infinite switching frequency. But, for practical system, sliding path will not travel exactly on the desired sliding plane due to switching nature and infinite switching frequency. This switching imperfection will cause an unwanted parameter in the sliding surface known as chattering as shown in Fig. 4(b) [9]. If this chattering phenomenon is not controlled, then the converter system will get high switching oscillation. Due to this chattering phenomenon, the converter performance is affected with high switching losses, hysteresis and eddy current loss, and EMI issues.

The reason for introducing HM based SMC is to reduce the chattering phenomenon by proper designing of hysteresis band within the boundary limits $S = \delta$ and $S = -\delta$ as shown in Fig. 5.

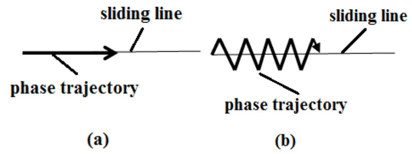

Fig. 4 – Three-linear structure trajectory under DCM operation.

The following control function is necessary for the implementation of HMSMC.

$$u = \begin{cases} \mathbf{1} \ \rightarrow \ \boldsymbol{u_B = 0} \ ; \ \boldsymbol{when} \ \ \boldsymbol{S > \delta} \\ \mathbf{0} \ \rightarrow \ \boldsymbol{u_B = 1} \ ; \ \boldsymbol{when} \ \ \boldsymbol{S < \delta} \\ \mathbf{0} \ \rightarrow \ \boldsymbol{u_B = 0} \ ; \ \boldsymbol{when} \ \ \boldsymbol{S < \delta} \end{cases}$$

Where δ is a positive quantity with small value which indicates the limits of hysteresis band (both upper and lower limits) and 2δ is the total value of positive quantity between the upper and the lower limits of hysteresis band width in the sliding plane. In this HMSMC, switching takes place on the limits between S =± δ, with a controlled switching frequency range according to the slopes of state variables. Sliding path is limited with a total bandwidth of 2δ in the sliding surface of S = 0.

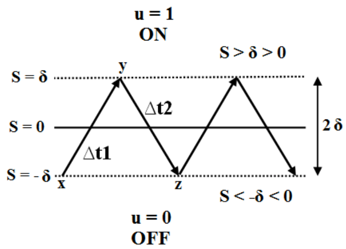

Fig. 5 – Phase trajectory for SMC using hysteresis modulation technique.

In Δt_1, the sliding function S varies from point x to y and y to z in between –δ to 0 and 0 to +δ [7]. The switching frequency is attained from Fig. 5 with the assumption of state variable controlled path being constant, nearer to the sliding plane S = 0 and represented by

$$f_{swit} = \frac{1}{\Delta t_1 + \Delta t_2}, \tag{11}$$

where Δt_1 and Δt_2 are the ON and OFF time of the converter switches.

The equation of Δt_1 is given by

$$\Delta t_1 = \frac{2\delta}{\dot{S}_{u\to 1}} \qquad \Delta t_1 = \frac{2\delta}{\lambda_1}. \tag{12}$$

For conduction OFF time Δt_2 is given by

$$\Delta t_2 = \frac{-2\delta}{\dot{S}_{u\to 0}} \qquad \Delta t_2 = \frac{-2\delta}{\lambda_2}. \tag{13}$$

$\lambda_1\lambda_2$ [lambda$_1$and lambda$_2$] are the parameters, which are used for obtaining the switching frequency in HMSMC.

$$\lambda_1 = \frac{K_1}{L_{in}}\left[V_{c1}+V_{c2}-V_{c1ref}-V_{c2ref}\right]-\frac{K_2}{C_1}\left[V_o-V_{ref}\right]-\frac{K_3}{C_2}\left[V_o-V_{ref}\right]+\frac{V_{rec}}{L_{in}}>0$$

$$\lambda_2 = \frac{K_1}{L_{in}}\left[V_{c1}+V_{c2}-V_{c1ref}-V_{c2ref}\right]-\frac{K_2}{C_1}\left[V_o-V_{ref}\right]-\frac{K_3}{C_2}\left[V_o-V_{ref}\right]$$

$$+\frac{K_1}{L_{in}}\left[V_{c1}+V_{c2}\right]+\frac{K_2}{C_1}\left[i_{Lin}-i_p\right]+\frac{K_3}{C_2}i_{Lin}+\frac{V_{rec}}{L_{in}}<0$$

The switching frequency is obtained by substituting the above two parameter values in eqs. (12) and (13) with the assumption that initially the converter has zero inductor current (i_{Lin} = 0). The switching frequency is obtained as

$$f_{swit}=\frac{1}{\Delta t_1+\Delta t_2},$$

$$T_{swit}=\frac{2\delta}{\frac{K_1}{L_{in}}\left[V_{c1}+V_{c2}\right]+\frac{K_3}{C_2}\left[V_o-V_{ref}\right]}.$$

Switching frequency of the converter is given by

$$f_{swit}=\frac{\frac{K_1}{L_{in}}\left[V_{c1}+V_{c2}\right]+\frac{K_3}{C_2}\left[V_o-V_{ref}\right]}{2\delta}.$$

It is interesting to note that the switching frequency (f_{swit}) depends upon the following parameters: sensed output voltage (V_o), capacitor voltages V_{c1} and V_{c2}, and input inductor L_{in} and sliding coefficients.

$$\delta=\frac{\frac{K_1}{L_{in}}\left[V_{c1}+V_{c2}\right]+\frac{K_3}{C_2}\left[V_o-V_{ref}\right]}{2f_{swit}}.$$

From the above equation, the switching frequency of the converter is inversely proportional to hysteresis bandwidth (δ) and it should be controlled based on δ.

4. SIMULATION RESULTS

The transient performance of the converter with HMSMC is simulated and evaluated using Matlab/Simulink [15]. Steady state and improved dynamic response of the converter is attained under different operating conditions by the proper selection of sliding coefficients K_1, K_2, and K_3.

Table 1

Simulation Parameters

Parameter	Symbol	Value
Input voltage	V_{in}	220 V
Output voltage	V_o	48 V
Inductor	L_{in}	45 µH
Capacitors	C_1,C_2	2200 µF
switching frequency	f_s	50 kHz
Load Resistance	R	1.7 Ω
K_1	Sliding gain	500
K_2	Sliding gain	2.5
K_3	Sliding gain	2.5
Efficiency	□ %	92 %

In this controller, the sliding coefficient values K_1, K_2, and K_3 are tuning parameters. It is advisable to choose the sliding co-efficient values K_1, K_2, and K_3 to agree with fast dynamic response and stability. The sliding coefficients K_1, K_2, and K_3 are selected by repetitive procedure until the transient response is adequate to obtain the better dynamic performance, and it is verified by Matlab/Simulink simulation. Sliding coefficients are evaluated by iterative method for simulation (K_1 = 500, K_2 = 2.5, and K_3 = 2.5).

Converter performance is validated against a variation occur at supply and load side and also for non-linear parameter variations. Simulation is done with converter with circuit parameters listed in Table 1.

Figure 6 indicates that the variation in the output voltage of HMSMC with Three Level ac-dc converter. From this figure, output voltage variation occurs at 0.6 s due to increasing the input voltage in a step manner from 220 V to 260 V. There is a small overshoot of 0.2 V occurs at output side and the converter settled down with very minimum time duration of 4 ms when line voltage changes from 220 V to 260 V. From this figure, it is clear that the output voltage is maintained 48 V even for wide changes occurring online side.

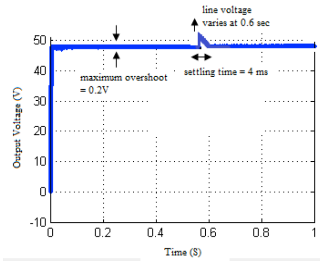

Fig. 6 – Sudden change in output voltage when a step change occurs in input voltage from 220 V to 260 V.

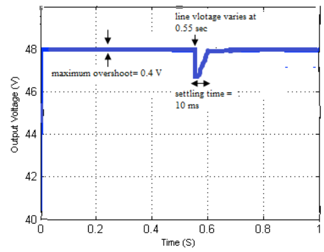

Fig. 7 – Sudden change in output voltage when a step change occurs in input voltage from 220 V to 190 V.

Figure 7 indicates the sudden change in output voltage for the converter under another decreasing of input voltage from 220 V to 190 V. It is interesting that the output voltage variation occurs at 0.5 s with overshoot of 0.4 V and the converter is settled down with very less time duration of 10 ms.

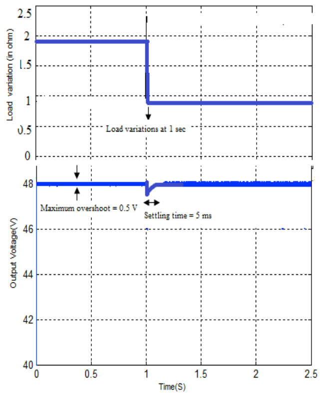

Fig. 8 – Output voltage when load mutation occurs from 1.7 Ω to 0.86 Ω.

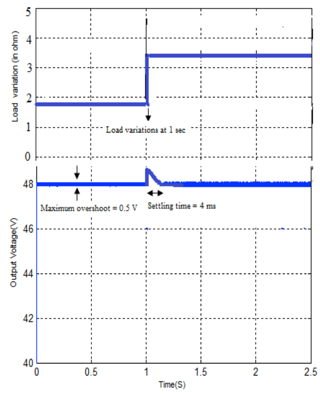

Fig. 9 – Output voltage when load mutation occurs from 1.7 Ω to 3.4 Ω.

Output voltage variation occurs at 1 second with decreasing load resistance is shown in Fig. 8. It is noted that load voltage is quickly settled with an overshoot of 0.5 V even though variations occur in load resistance and the converter reaches steady state with less time duration of 5 ms which know as settling time of the converter against load variation. Figure 9 shows that the output voltage variation occurs at 1 s with increasing load value. From this figure, it is concluded that the converter reaches steady state with a small maximum overshoot of 0.5 V and less settling time duration of 4 ms under decrease in loading condition.

Simulated result in Fig. 10 shows the output response of the converter for the variations in capacitor values. The HMSMC is a very effective method to suppress the effect of capacitance variation which leads to reduce the converter dynamic performance. By using HMSMC, capacitor variations do not affect the converter performance and the output response is settled down with a minimum time duration of 5 ms. Figure 11 shows the load side performance of the converter for the variations in the inductor values from 1 µH to 5 µH and this parameter variation does not affect the converter steady state and dynamic performance due to the effective control using HMSMC.

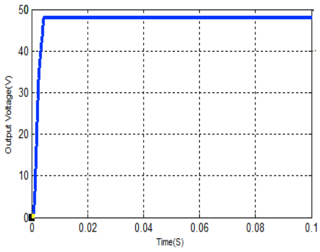

Fig. 10 – Output voltage when capacitor variation takes place.

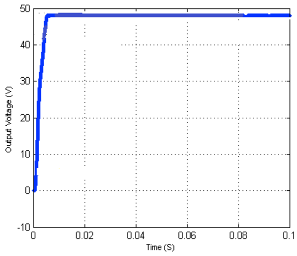

Fig. 11 - Output voltage when inductor varies from 1 µF to 5 µF.

Table 2

Large signal transient parameters under line, load, and non-linear parameters variations

Parameter	HM based SMC				
	Value	**V_o(V)**	**Time duration for settling**	**Peak over shoot**	**Rise time**
Line variation	220 V-260 V	48	4 ms	0.2V	5 ms
	220 V-190 V	48.02	10 ms	0.4V	4 ms
Load variation	1.7 Ω–3.4 Ω	48	4 ms	0.5V	4.5 ms
	1.7 Ω-0.85 Ω	48	5 ms	0.5V	5 ms
Inductor variation	1 µH	48.01	6 ms	0.4V	4 ms
	5 µH	48	5 ms	0.5V	

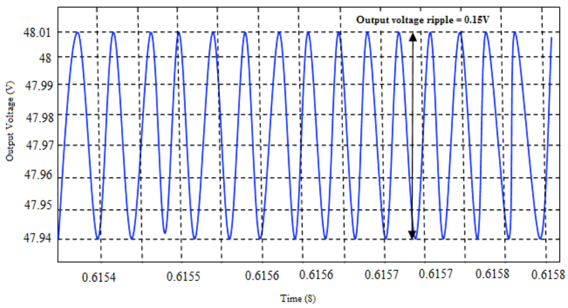

Fig. 12 – Phase trajectory for SMC using hysteresis modulation technique.

Figure 12 shows the instantaneous output voltage in the steady state. From this figure, it is evident that the converter reaches steady state with a very small ripple content of 0.15 V. Table 2 shows the numerical value of converter steady state and transient parameters using HMSMC.

This hysteresis modulation-based SMC is operating within switching frequency range based on the bandwidth of the controller. Bandwidth of the controller is designed with respect to sliding path for all possible conditions of SMC.

From the view of steady state analysis, efficiency of three level ac-dc converter is evaluated and measured. It is observed that the converter maximum efficiency is 92 %. Average efficiency of the converter is 90.2 %. Since this converter is power factor correction converter, power factor improvement is imperative to meet the power quality standards. From simulation, the obtained power factor value is 0.972 with a less THD phenomenon.

5. CONCLUSIONS

Steady state and transient behavior of the converter was analyzed and presented in this paper. The converter is operating under highly non-linear dynamic behavior due to the variations that occurred in line side, load side, and non-linear parameters. This paper was focused on eliminating the system disturbances by introducing HMSMC. In this paper, the design and suitability of HMSMC for the converter was successfully analyzed to obtain the improved steady state and transient response under various operating conditions. Also, state space averaged model of the converter was derived to design HM based SMC. By using valid simulated results, it has been proved that the converter has good steady state and transient performance using HMSMC against variations occurring at supply and load side and circuit components variations.

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