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WIDER RANGE OF TUNING THE PROPOSED VSC-HVDC SYSTEM FOR IMPROVED CONTROLLER PERFORMANCE

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ABSTRACT

Tuning of the Voltage Source Converters, High Voltage Direct Current (VSC-HVDC) controllers is a critical undertaking continuously carried out in power system operation to ensure system stability is kept under control while making maximum utilization of the plant output. The transfer functions for the controllers are mathematically derived using the control loops and properly tuned using the modulus optimum criterion (MOC) and the symmetrical optimum criterion (SOC) for improved controller performance. In this study, tuning of the controllers is carried out through the act of balancing the system response and its stability by selecting the proportional gain and time constant carefully based on the desired application. The vector control is utilized in this work due to its inherent ability to independently control active and reactive power between the converters and the grid. The stability of a power system relies on the symmetrical distance (a) selected. Previous researches advocated for VSC-HVDC control system to have the symmetrical distance selected between 2 and 4 respectively when using the SOC and the MOC tuning techniques respectively. However, the theoretical analysis and simulation results in this paper shows that for quick system response time and stability, the value of 'a' is selected as 8 when tuning the inner current controller by MOC and a=2 while tuning the DC voltage regulator with SOC. The model developed is implemented in DigSilent Power Factory and the results indicate that with proper tuning of the proposed controllers and based on the method of tuning, some good *performance improvement in the controllability of DC voltage, active and reactive power is achievable.*

Key words: Improved controller performance, two loop system, Tuning techniques, VSC-HVDC.

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1. INTRODUCTION

Voltage Source Converter, High Voltage Direct Current (VSC-HVDC) System is relatively newer transmission technology of choice for many power utilities and has recently been adopted globally due to number of factors one being its independence of ac network and second is the ability to independently control active and reactive power between the converters and the grid. Other reason why the technology continues to receive a lot of attention is because of its modularity, low power operation and ability of power reversal [1]. VSC-HVDC transmission systems are used for connection of weak system such as a wind farm. Compared to other transmission technology such as Line commutated converter (LCC-HVDC), VSC-HVDC has better fault ride through capability and has the capacity to restart the network after fault is cleared thus minimizing the down. This translates into increased revenue. The technology has also been well accepted globally and a country like Northern Norway has a larger section of its 132KV network constructed in VSC-HVDC technology and has plan of integrating above 4GW of wind power to the conventional grid [1]. VSC-HVDC technology is commercially available through the trade names HVDC light [2] and HVDC Plus (power link universal systems) [3] by ABB and SIEMENS. Figure.1 Shows the VSC-HVDC transmission system. It consists of two main components (two loop systems) that are of interest in this study though it has other items that are equally important such as filters, inductors, converter transformers, DC capacitors and DC transmission lines. The two loop systems are the inner control loop and the outer control loop. The inner current control loop is also known as vector current control while the outer controller consists of active and reactive powers, DC and AC voltage controllers and the frequency controllers. Only two controllers can be selected at any given time for each converter and the selection for each controller largely relies on the application desired by the system controller on duty.

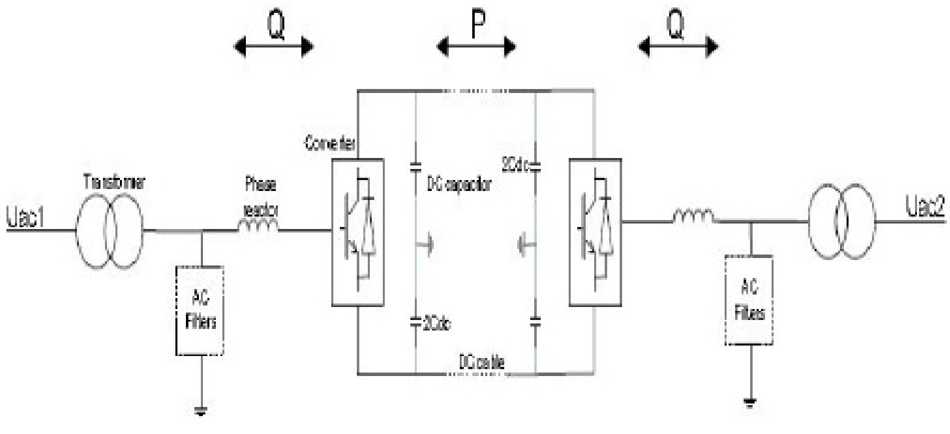

Figure 1 VSC-HVDC based system

Basically, VSC-HVDC system involves the study of the control system with its controllers. The tuning of the VSC controllers is based on the principle adopted for the basic electrical derives [4]. The inner current control loop controls the current that usually flows through the phase reactors while the outer controller produces the reference currents for the inner current control. However, most of the researchers have restricted themselves to using the tuning techniques based on SOC and MOC by selecting the symmetrical distances between (a=2) and (a=4) respectively. In order to have a system that has fast response and yield maximum output than the one currently available, it is critical to explore other values of symmetrical distances. In this study, tuning of the inner current controller and the DC voltage controllers are robustically selected using the two tuning techniques and wider range of parameters are selected and compared to find out the best system response taking into account of a compromise between overshoot, rise time, settling time and phase margin.

The parameters are selected to accommodate the best range of operating conditions as will be seen later in this work. As previously mentioned, tuning of a controller is a compromise between many factors and it has to be done with the purposes of ensuring that the system stability is upheld. Normally, the control loops are nonlinear in nature and intelligent selection of the parameters should be manifested in their ability to allow wider range of operations. This paper presents two comparison methods for tuning of controllers namely; the optimum modulus criteria and symmetrical tuning criteria that are used for the sole purpose of establishing the tuning criteria that caters for both system response and the optimal output. The two tuning methods are used for tuning of DC voltage controller and inner current controller through a wider selection of parameters to accommodate diverse operating conditions.

2. VSC-INNER CURRENT CONTROLLER

The inner current controller usually controls the reference current values from the outer controllers and generates voltage reference values. This current flows through the phase reactors and is controlled according to the reference current values from the DC outer voltage loop and therefore the tuning of the PI controllers which is basically the PQ controllers is the core function of the VSC-HVDC control system. According to [5] the inner current control is implemented in ad_q-coordinate system. The phase locked loop (PLL), which provides the reference angle of the d_q transform, normally enables the d-axis to be aligned with the voltage vector at the point of common coupling (PCC) so as to achieve an independent control of real and reactive power [6]. The inner current control loop has two PI regulators each for the d and q axis reference currents. The input current to the rectifier and the output current from the inverter is measured and compared with the reference current values and the error (Err) signal is fed to the controllers (regulators) to produce switching signals to the PWM converters. The PWM transmit signals to the system as shown by the current control loop in figure.2.

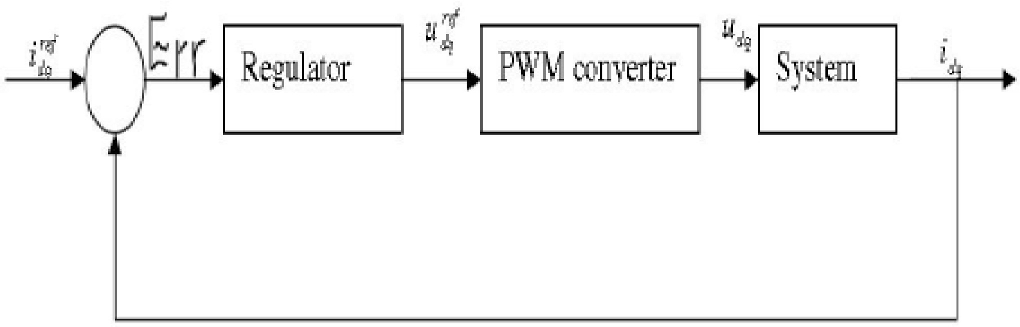

Figure 2 The inner current control loop

As a result of the d_q transformations produced by the DC vectors, the PI is able to reduce the steady state error signal to zero. The PI regulator is represented by the equation.1 below;

$$K_p\left(1+\frac{1}{sT_i}\right) \tag{1}$$

The PWM produces the output voltage. In PWM the switching frequency is expected to be much larger than the system frequency. In this study, converter switching frequency of 5000Hz is chosen. The high frequency chosen reduces the size of the filters required to eliminate the harmonics generated subsequently reducing the cost of the converter.

2.1. Inner Current Controller by Modulus Optimum Criteria

Tuning of the inner current controller is done with the aim of achieving fast system response towards the inner loop based on the optimum modulus criterion. This method is implemented when the controlled system has one dominant time constant and the other minor time constant. The dominant pole is cancelled by the controller zero to arrive at a standard transfer function. This method is selected because of its simplicity and fast response at tracking the reference value. From figure.2, the open loop transfer function of the system is obtained through the modulus optimum criteria.

$$G_{ol}(s) = K_p\left(\frac{1+ST_i}{ST_i}\right)\left(\frac{1}{1+ST_i}\right)\left(\frac{1}{R+SL}\right) \tag{2}$$

Eliminating the zero of the regulator yield;

$$T_i = \tau = \frac{L}{R} \tag{3}$$

$$G_{ol}(s) = K_p\left(\frac{1+ST_i}{ST_i}\right)\left(\frac{1}{1+ST_i}\right)\left(\frac{1}{R}\right)\left(\frac{1}{1+ST_i}\right) \tag{4}$$

After cancelling the dominant pole and zero of the controller, it gives rise to a second order close transfer function of the form shown below.

$$G_{cl}(s) = \frac{KP/R}{ST_i(1+ST_a)+KP/R} \tag{5}$$

On further simplification of the above equation gives;

$$G_{cl}(s) = \frac{KP/RTiTa}{S^2+\frac{S}{Ta}+\frac{KP}{RTiTa}} \tag{6}$$

From the equation 6, we can get the undamped natural frequency as;

$$\omega n = \sqrt{(\frac{KP}{RTiTa})} \tag{7}$$

To get the damping ratio, equation 6 is compared with a standard second order equation below;

$$\frac{C(s)}{R(s)} = \frac{\omega^2 n}{S^2+2\xi\omega^2 n+\omega^2 n} \tag{8}$$

Equating the damping factor and the undamped natural frequency gives;

$$2\xi\omega^2 n = \omega n = \sqrt(\frac{KP}{RTiTa}) \tag{9}$$

From the equation 9 above we get the damping ratio;

$$\xi = \frac{1}{2}\sqrt(\frac{RTi}{KpTa}) \tag{10}$$

In this study;

R=0.20253Ohms; L=12.9mH; thus, $Ti = \frac{L}{R} = 0.063694S$

For a=2;

$$T_a = \frac{T_{eq}}{2} = 0.0001s$$

Where T_a=Average time delay of the converter

$$K_p = \frac{TiR}{4\xi Ta} = \frac{0.063694 \times 0.20253}{4 \times 0.707^2 \times 0.0001} = 64.51 \tag{11}$$

The final closed loop transfer function becomes;

$$G_{cl} = \frac{50.02 \times 10^6}{S^2 + 10^4 S + 50.02 \times 10^6} \tag{12}$$

From equation 12 above, response for the inner current controller can be represented on a graph as will be seen later in this work. Similarly, other parameter with different values of symmetrical distance (a) are calculated and inserted in table 1 below.

Table 1 Calculated parameters for the Inner current controller.

a	Ti	Kp	Ta
2	0.063694	64.51	0.0001
3	0.063694	96.3	0.000067
4	0.063694	129	0.00006
5	0.063694	161.1	0.00004
6	0.063694	195.5	0.000033
8	0.063694	258	0.000025

3. VSC OUTER CONTROLLERS

Normally, a VSC-HVDC system has four outer controllers. In this study case, only one outer controller is discussed. This is the DC voltage controllers. Usually a two terminal VSC-HVDC system has a rectifier and an inverter. The rectifier station operates as a power control mode to control active power drawn from the AC grid and at the same time controls the reactive power compensated to the grid. It also has the capability to control AC grid voltage directly. The inverter station has the responsibility of ensuring that the DC link voltage is maintained at the desired definite level otherwise the active power flow balance between the converters and the grid may result into power imbalance leading to system instability.

The outer controllers need to be properly tuned so that to damp the system oscillations and attain system stability. The outer controllers generate the reference d-component currents and q-component currents. The current values are later fed into the faster inner current controller which gives d-q component voltage values that are injected into PWM generator and into the system. In [7], all the outer controllers are implemented by a PI controller where the difference between the reference values and the actual value is fed into the controller as the d-q reference currents.

3.1. DC Voltage Controller

As previously mentioned, the inner current controller controls the currents based on the reference values generated from the DC voltage control loop. On the other hand, the DC voltage controller ensures regulation of active power and reactive power through the control of d and q axis components of current. Based on [8], the DC voltage controller has four parts that constitute the voltage loop, namely;

i. The PI controller $K_P(1+\frac{1}{s_{Ti})})$

ii. The inner current controller, $(\frac{1}{1+T_{eqs}})$

iii. The system, $\frac{3}{2}\frac{1}{C.S}\frac{Vd}{Vdc}$

iv. The measurement circuit is the feedback loop $\frac{1}{1+T_S s}$;

where Ts is the sampling time of the inner current controller. In order to derive the DC voltage control loop, some assumptions were made. Assuming a lossless converter, the power into the converter is equal to the power output from the converter. Therefore, based on this assumption, the two equations below hold true:

$$P=\frac{3}{2}V_d i_d \tag{13}$$

$$Q=-\frac{3}{2}V_d i_Q \tag{14}$$

Equations 13 and 14 indicate that, the active power is dependent on d-axis current while the reactive power is dependent on q-axis current. Similarly, the DC Power is given by;

$$P_{dc}=V_{dc} i_{dc} \tag{15}$$

Equating the active power equation 13 with the DC power equation 15 yields;

$$\frac{3}{2}V_d i_d=V_{dc} i_{dc} \tag{16}$$

Applying the Kirchhoff's current law at the node on the dc of figure. 2, yield the equation 17 below.

$$C_{dc}\frac{du}{dt}dc=i_{dc}-i_L \tag{17}$$

Where i_{dc}Converter output DC current, iL - DC current through DC link, C_{dc}- DC capacitor capacitance

Rearranging equation 17 becomes,

$$i_{dc}=i_L+C_{dc}\frac{du}{dt}dc \tag{18}$$

Substituting equation 18 to 16 yield;

$$\frac{3}{2}V_d i_d = V_{dc}\left(i_L + C_{dc}\frac{du}{dt}dc\right) \quad (19)$$

Using the basic Laplace transformation and solving for U_{dc} in eqn.19, we get

$$V_{dc} = \frac{1}{C_s}\left(\frac{3}{2}\frac{V_d i_d}{V_{dc}} - i_L\right) \quad (20)$$

The resulting block diagram of the dc voltage controller loop is illustrated in Figure.3. The disturbance introduced by iL can be eliminated by introducing a compensation term $\left(\frac{2}{3}\frac{V_{dc}}{V_d} i_L\right)$before the converter.

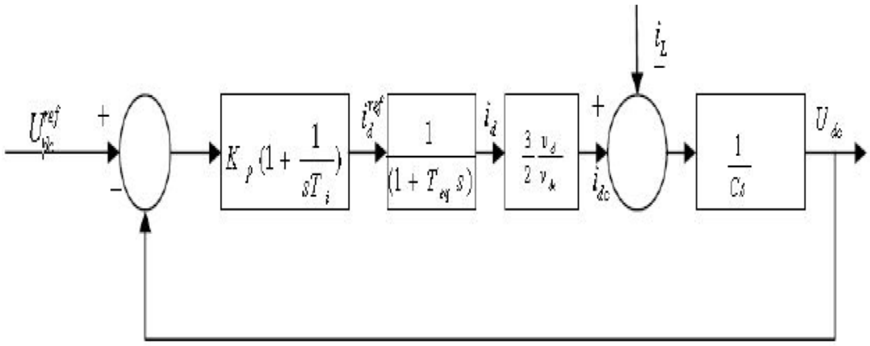

Figure 3 DC voltage control loop in dq axes

3.2. Tuning the DC Voltage Controller Using the Symmetrical Optimum Criterion

Tuning the PI controller can be attained using the modulus optimum criteria however, if one of the poles is adjacent to the origin or at the origin itself, the pole shift is insignificant. An alternative criterion to tune the controllers in this condition is given by the symmetrical optimum criteria. As in figure. 3, DC voltage controller loop has two poles at the origin and thus the optimum symmetrical tuning is used in this study to design the controllers' parameters. Various researches has been carried out concerning the tuning of the DC voltage controller based on optimum symmetrical tuning [9] and [10], as such, the equation below holds true.

$$Ti = a^2 T_{eq} \quad (21)$$

Ti is the proportional time constant. It has been argued in [9], that the symmetrical distance between $\frac{1}{Ti}$ to cross over frequency and $\frac{1}{T_{eq}}$ and cross over frequency must be within 2 and 4 for improved system response, however, in this study, wide range of values are selected for tuning of the PI controller and find out which of the values gives better system responses taking into consideration of a compromise between performances thus, the equivalent time delay T_{eq} due to the current control loop is given in equation below.

a=2;

$$T_{eq} = aT_a = a\frac{Ts}{2} = a\frac{1}{2fs} = 2 \times \frac{1}{2 \times 5000} = 0.0002 \quad (22)$$

Where fs is the switching frequency,

$$T_a = \frac{1}{2fs} \quad (23)$$

$1/_{2fs}$ is the inverse of the switching frequency.

If a=3 then,

$$\mathrm{T_{eq}} = 3 \times \frac{1}{2 \times 5000} = 0.0003 \quad (24)$$

$$\mathrm{T_i} = 3^2 \times 0.0003 = 0.002 \quad (25)$$

In this study, the parameters below were utilized based on the symmetrical optimum tuning. For a=2, the proportional gain becomes;

$$K_p = \frac{2}{3}\frac{V_{dc}}{aV_dT_{eq}} = 0.163 \quad (26)$$

From figure 3, K is given by:

$$K = \frac{2}{3}\frac{K_PV_d}{Vdc} = 0.137 \quad (27)$$

Now using the PI controller parameters, the overall closed loop transfer function for fig. 3, becomes,

$$G_{cl} = \frac{K + KT_is}{K + KT_is + TiCS^2 + TiTeqCS^3} \quad (28)$$

$$= \frac{0.1347 + 1.078 \times 10^{-4}s}{0.1347 + 1.078 \times 10^{-4}s + 4.315 \times 10^{-8}s^2 + 8.629 \times 10^{-12}s^3} \quad (29)$$

For $a = 3$;

$$Teq = 0.0003 \quad (30)$$

$$Ti = 3^2 0.0003 = 0.0027 \quad (31)$$

$$Kp = 0.07253$$

$$K = \frac{3}{2}\frac{KpVd}{Vdc} = 0.05993 \quad (32)$$

$$KT_{is} = 0.05993 \times 0.0027 = 1.6181 \times 10^{-4} \quad (33)$$

For a=4

$$Teq = 4 \times \frac{1}{2 \times 5000} = 0.0004 \quad (34)$$

$Ti = 0.0064$, $Kp = 0.0408$,$K = 0.03371$. Similarly, other parameters are calculated at various values of 'a' as shown in figure.2.

Table 2 Calculated parameters for the DC voltage controller.

a	Ti	Kp	K	KTi
2	0.0008	0.1632	0.1347	0.00011
3	0.0027	0.07253	0.05993	0.0001618
4	0.0064	0.0408	0.03371	0.0002157
5	0.0125	0.02611	0.02157	0.00027
6	0.0216	0.01813	0.01498	0.000324
8	0.0612	0.0102	0.00843	0.000432

4. METHODOLOGY

The schematic diagram of VSC-HVDC system control in figure.4 is modeled for simulation in this study by use of Digsilent software. Detailed analysis aimed at investigating the impact of the VSC-HVDC controllers tuning is carried out with various values of symmetrical distance (a) using the two previously mentioned tuning techniques. Enhanced tuning of the inner current vector controllers and the outer controller (DC voltage controllers) provides improvability in the control of active and reactive power and the DC voltage respectively both under normal operation and under fault condition. Therefore, it is important to select parameters that results into a system that conforms to the acceptable performance and indeed improved system performance for increased flexibility and sustainability of the network. The parameters adopted in this study are R=0.20253 Ohms, L=0.000053933 Farads, transformer rating= 100MVA, 230/45KV, converter rating=100MVA, DC overhead line length=111KM.

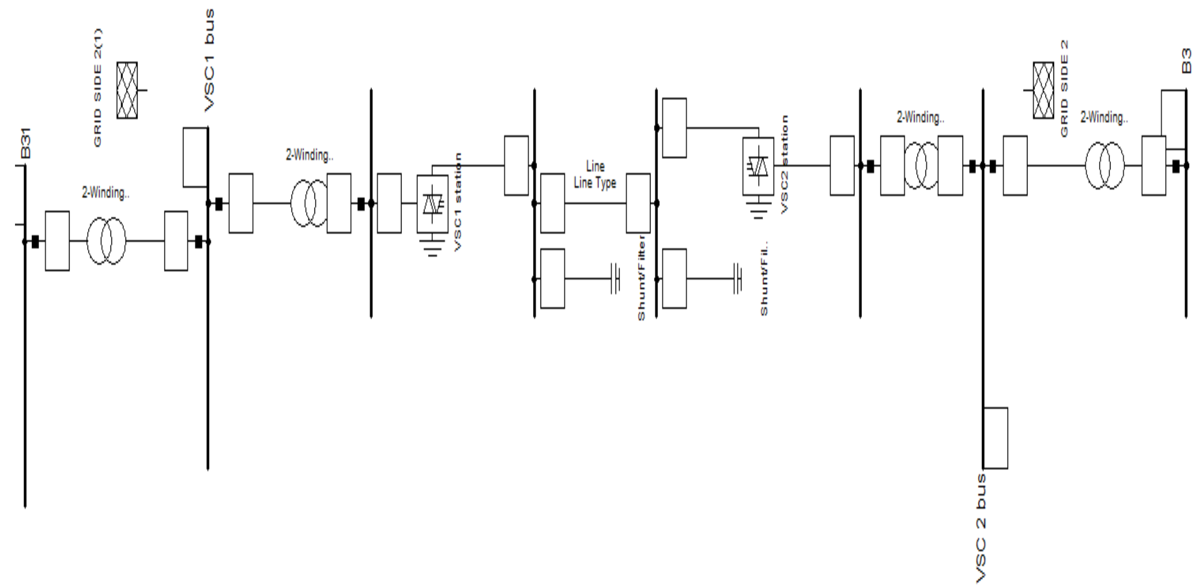

Figure 4 VSC-HVDC System control

Two tuning methods namely modulus optimum criteria and the symmetrical optimum criteria have been discussed in detail. The two methods are compared to find out how effective they are in controlling the inner current vector controller and the DC voltage controller. Adequate design of the former and the latter makes it possible to independently control the active and reactive power independently and maintain the desired voltage levels within the power network. In order to realize the above requirements, various parameters for DC voltage controller and the inner current vector controller were calculated using the two tuning techniques. Graphs showing comparisons for various parameters selected are presented in the next section.

5. RESULTS AND DISCUSSION

In this study, two tuning techniques are discussed. The analytical expressions for the inner current vector controller and DC voltage controller are presented in the form of second order closed loop systems using the two tuning techniques with diverse values of symmetrical distance selected. Simulations generated as a result of wider tuning of the inner current controller by modulus optimum criteria (MOC) and the DC voltage controller by symmetrical optimum criterion (SOC) are shown in the sections that follows.

5.1. Tuning of Inner Current Controller by Modulus Optimum Criterion (MOC)

The simulations results are shown in figures.5-15 respectively.

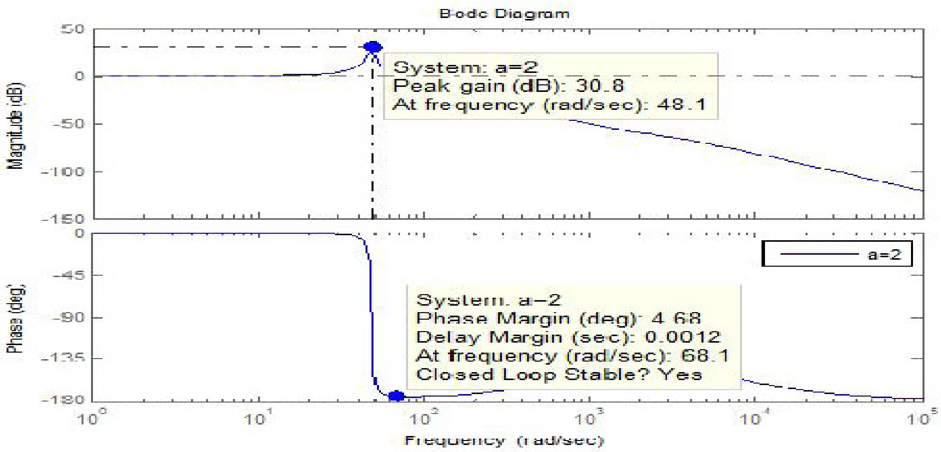

Figure 5 Bode plot of inner current controller with a=2

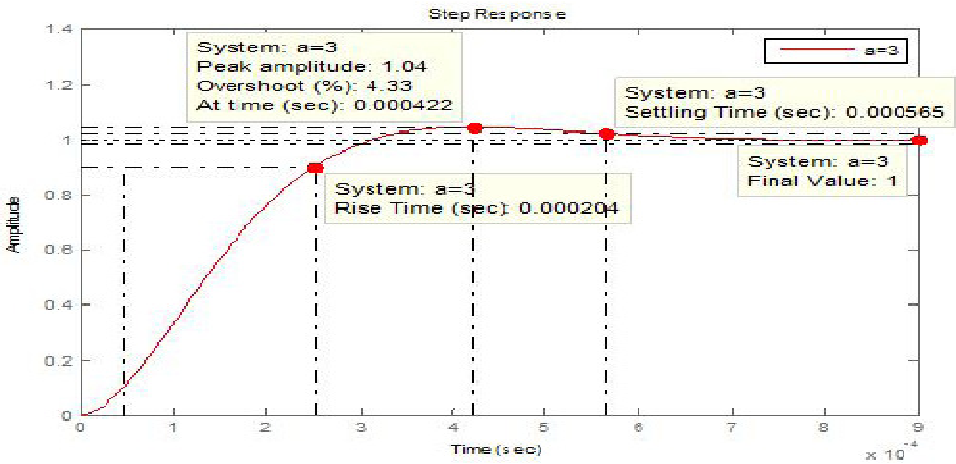

Figure 6 Step response of inner current controller with a=3

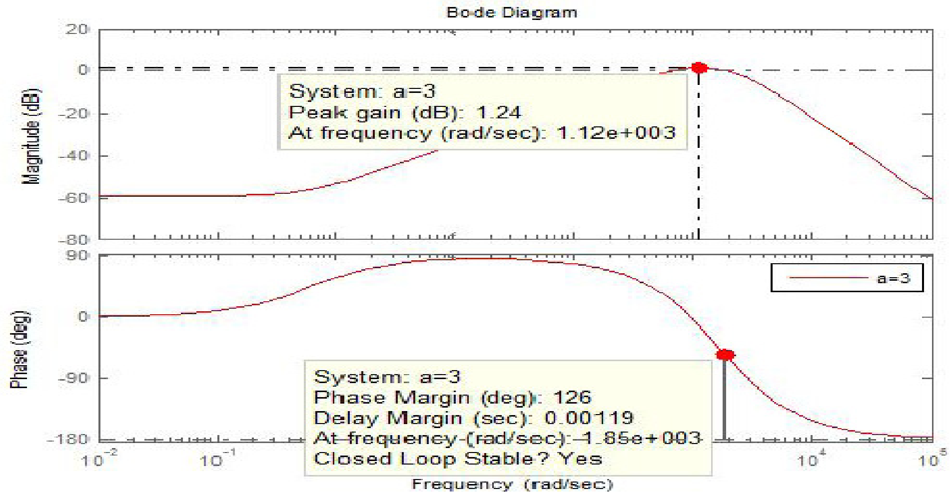

Figure 7 Bode plot of inner current controller with a=3

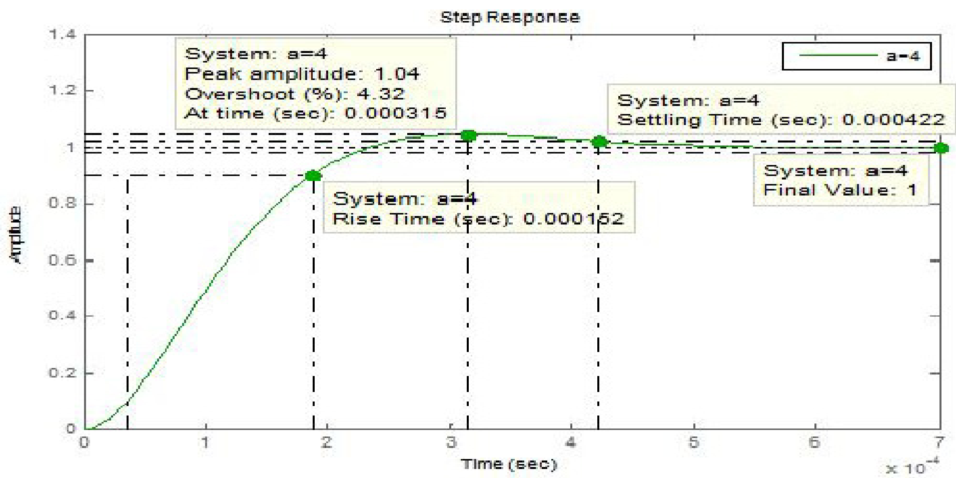

Figure 8 Step response of inner current controller with a=4

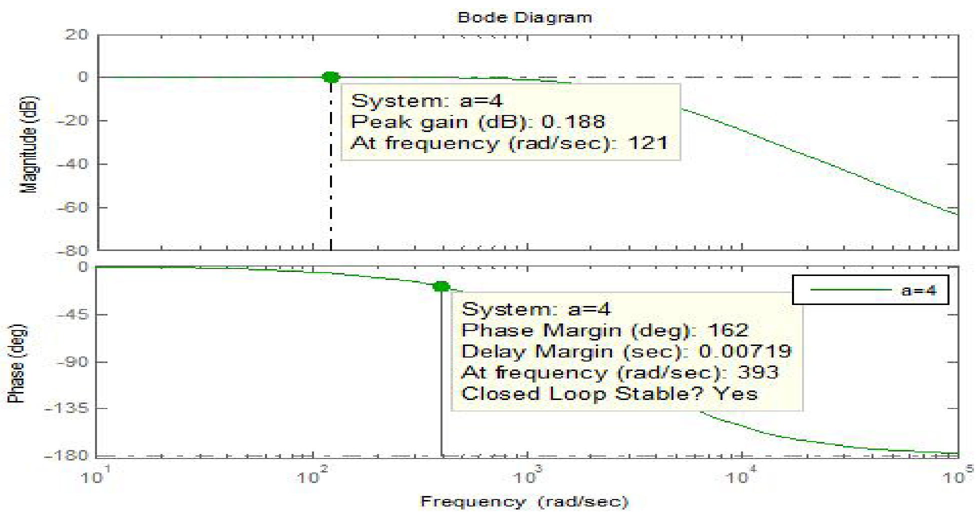

Figure 9 Bode plot of inner current controller with a=4

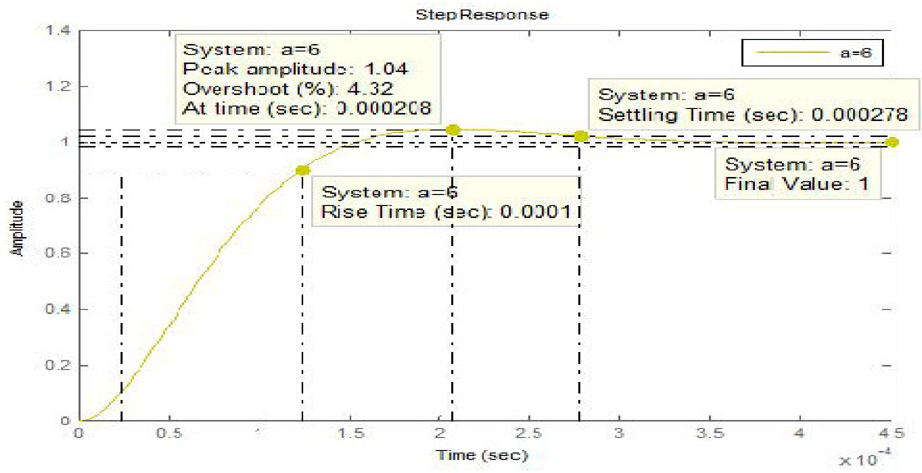

Figure 10 Step response of inner current controller with a=6

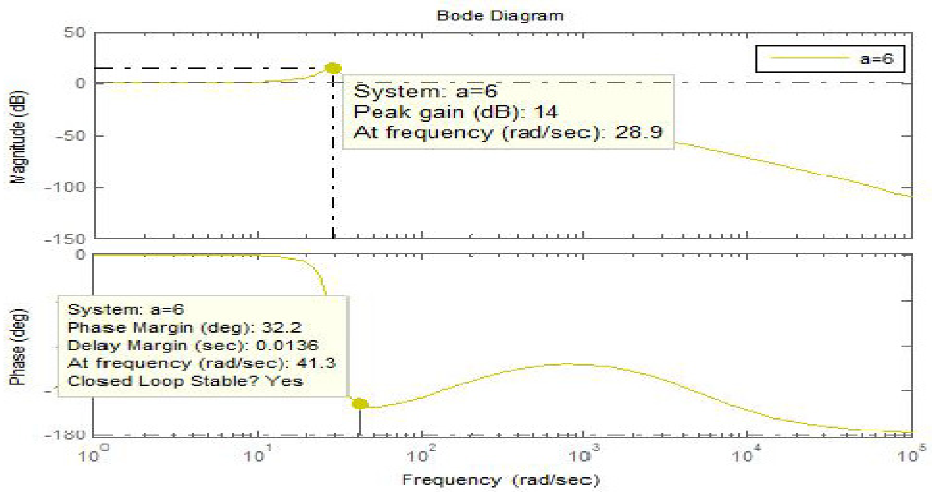

Figure 11 Bode plot of inner current controller with a=6

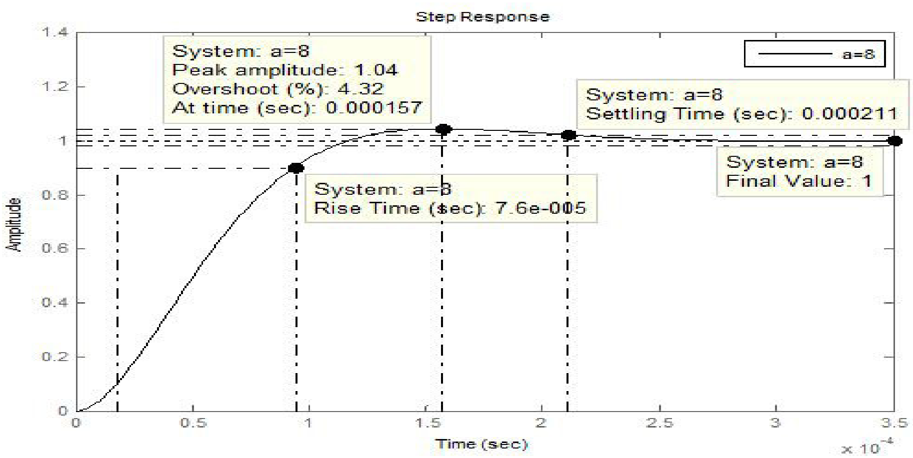

Figure 12 Step response of inner current controller with a=8

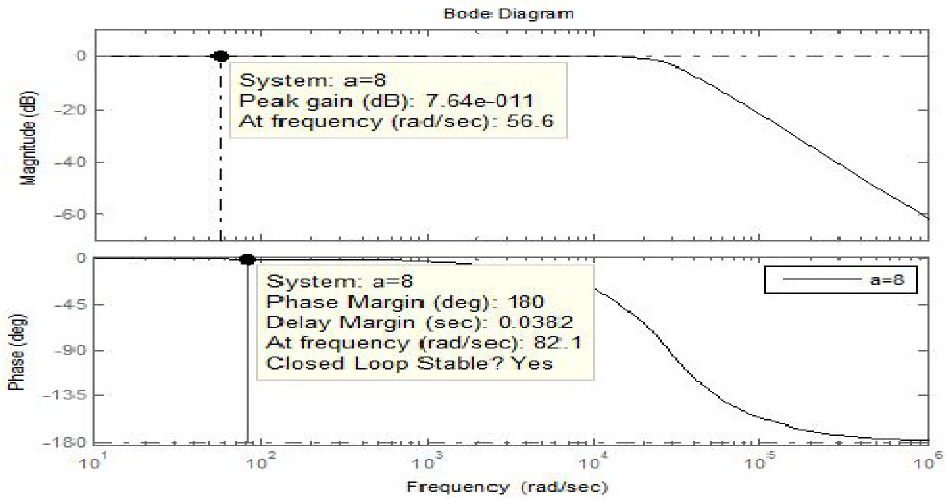

Figure 13 Bode plot of inner current controller with a=8

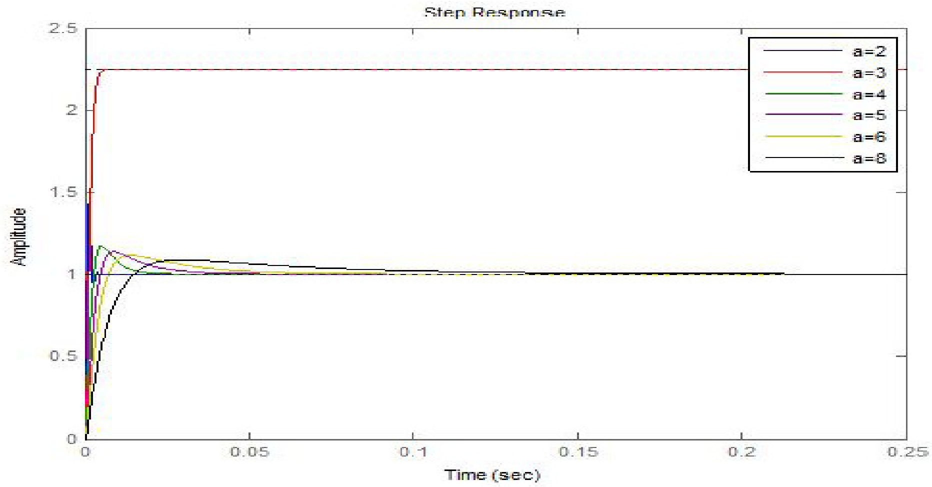

Figure 14 Step response of DC voltage controller with different values of 'a'

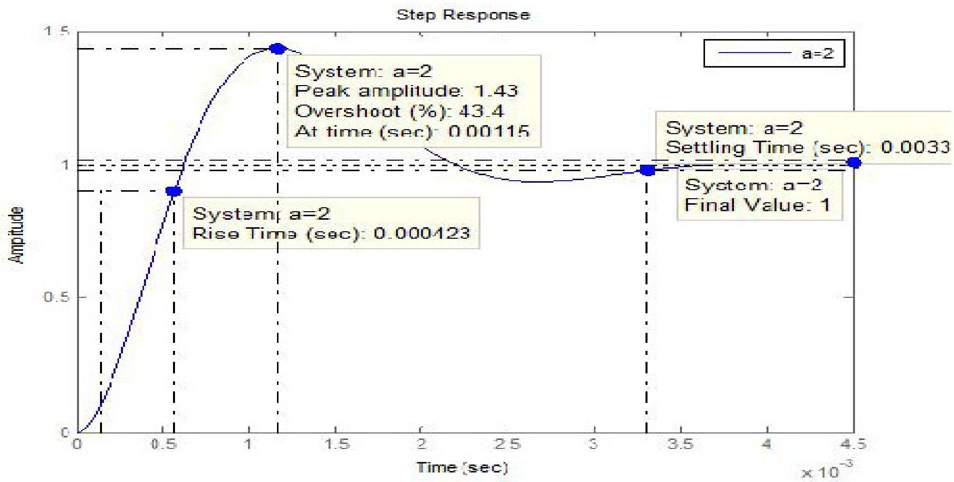

Figure 15 Step response of DC voltage controller with a=2

5.2 Tuning of the DC Voltage Controller using the Symmetrical Optimum Criterion (SOC)

The simulation results are shown in figures 16-22 respectively.

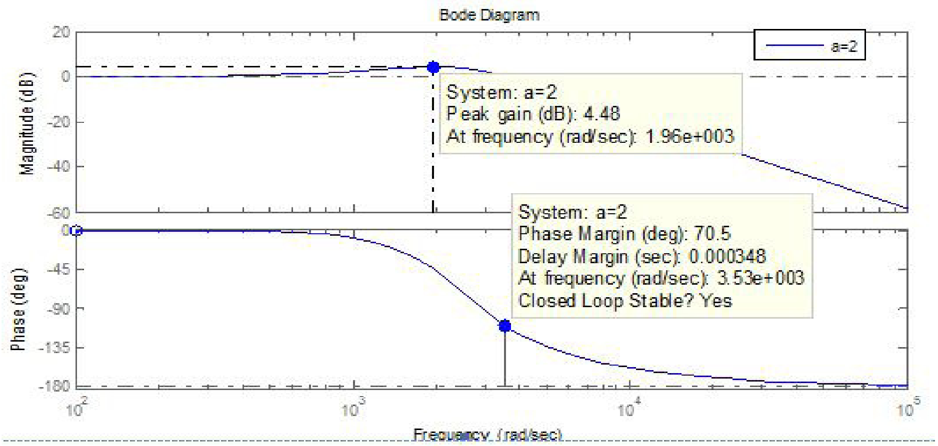

Figure 16 Bode plot of DC voltage controller with a=2

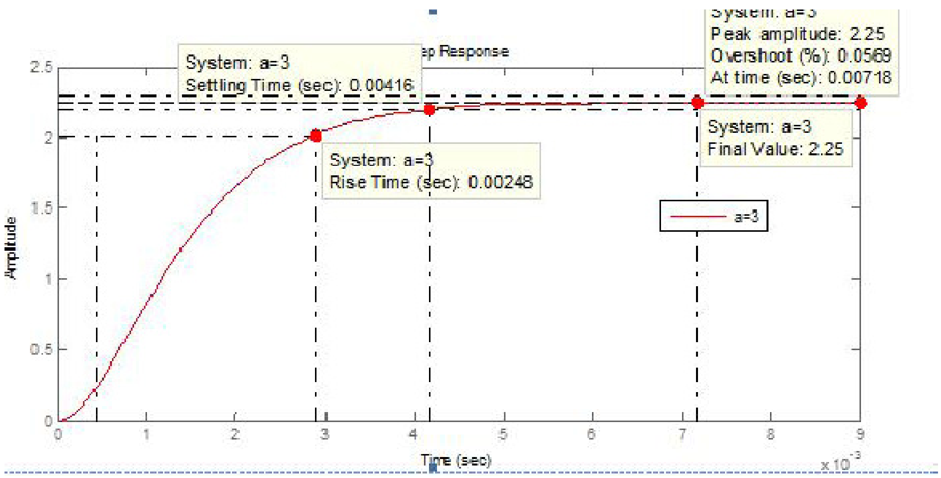

Figure 17 Step response of DC voltage controller with a=3

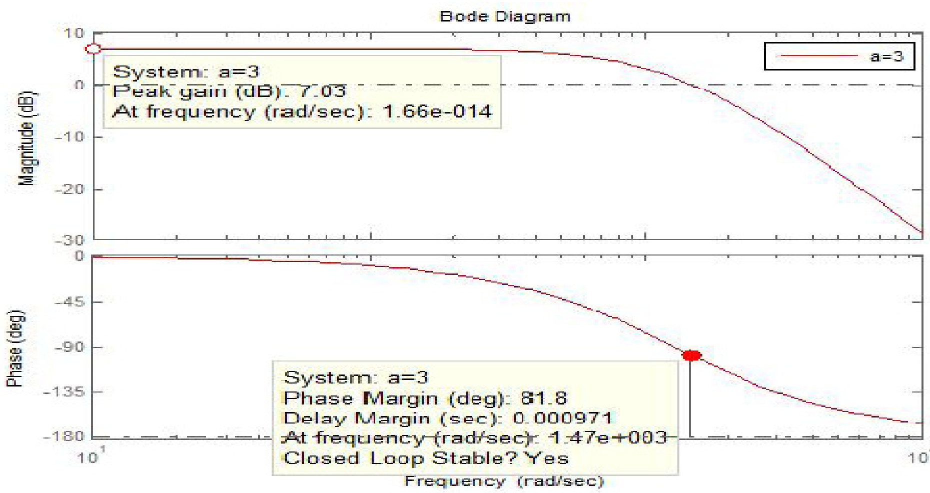

Figure 18 Bode plot of DC voltage controller with a=3

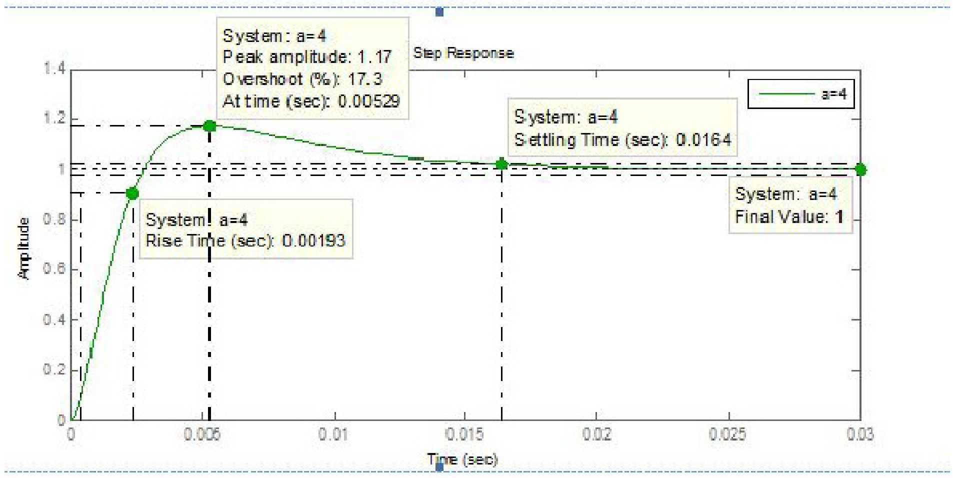

Figure 19 Step response of DC voltage controller with a=4

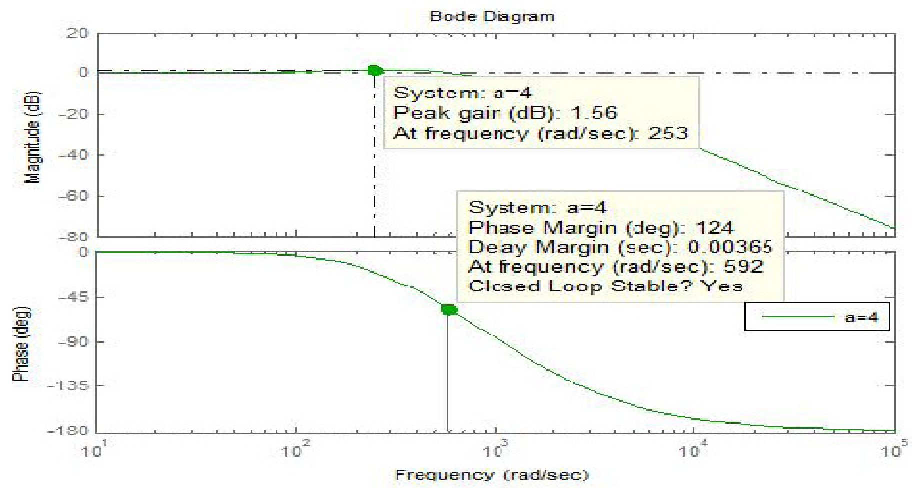

Figure 20 Bode plot of DC voltage controller with a=4

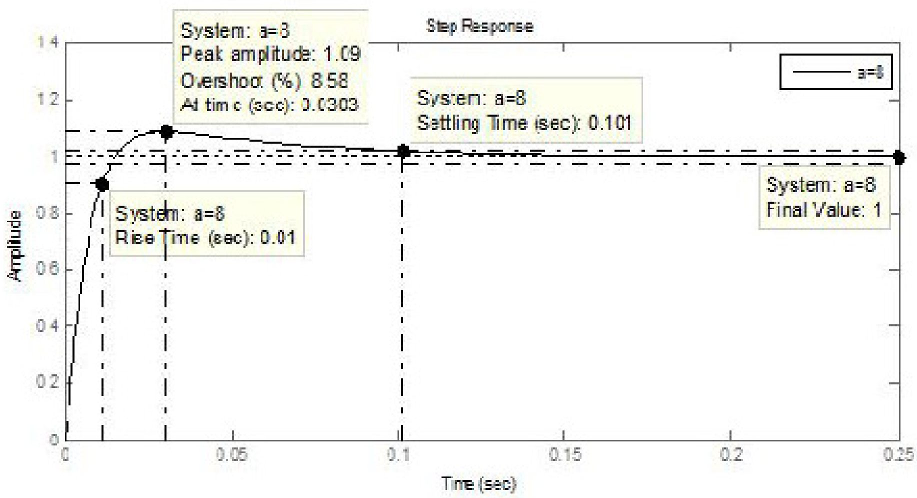

Figure 21 Step response of DC voltage controller with a=8

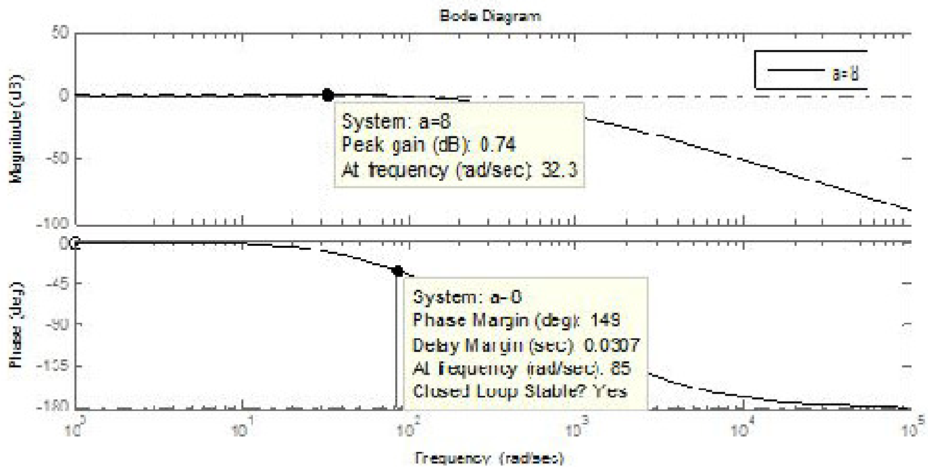

Figure 22 Bode plot of DC voltage controller with a=8

The figures 5-15 shows the bode plots generated through tuning of the inner current controller through modulus optimum criterion for diverse values of symmetrical distance (a) ranging from 2 to 8. Comparing the characteristics of the inner current controller based on overshoot, rise time, settling time, phase margin, cross over frequency and the peak gain for various values of symmetrical distance it is crystal clear that at a=8, the system is stable and damps out the oscillations within a very short duration. Similarly, figures 16-22 shows the behaviour of the DC voltage controller when tuned using symmetrical optimum criterion at different values of symmetrical distance. Further comparison of the behaviour of the DC voltage controller with diverse values of symmetrical distance shows that at a=2, the system is stable and damps out the oscillations very fast. Though the overshoot is higher, the system settles quickly thus attaining the much desired system stability.

6. CONCLUSION

From the theoretical analysis and simulations results, the following conclusions can be drawn:

It is evidently shown that, using the modulus optimum criterion, the most appropriate symmetrical distance for tuning the DC voltage controller is at a=2. Despite having a higher overshoot and small phase margin, the system rise time and settling time is low thus giving the best stability point. However, by using the inner current controller, the overshoot can be reduced by selecting higher values of symmetrical distance such as a=8 that gives a small overshoot, swift rise time and shorter settling time that are critical characteristics for system stability.

Researcher such as [11] concluded that based on symmetrical optimum criterion (SOC) and for stable system with good system response time then, the symmetrical distance should be between

$Ti = 2^2 Teq, for a = 2$ and $Ti = 4^2 Teq, for a = 4$

However, in this analysis, it has been shown that tuning of the inner current controller based on modulus optimum criterion yield the best system response time and stability at a=8. Though the overshoot for various values of symmetrical distance is almost the same, the time at which it occurs for a=8 is the smallest. Similarly, from the same results it is shown that its settling time is the smallest and the system is the most stable compared to other values of symmetrical distances.

From the analysis carried out in this study, the tuning of the controller largely depends on the symmetrical distance selected based on the application that is desired. Further studies need to find out whether wider values of symmetrical distance have negative influence on the converter losses and establish general rules of tuning such controllers for improved performance.

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