Control of Series HVDC Bridges with Different Firing Angles

HUSSEIN. D. AL-MAJALI
Department of Electrical Engg, Faculty of Engg
Mu'tah University, Al-Karak
JORDAN
halmajali@mutah.edu.jo

SULAIMAN. M. AL-DHALAAN
The General Organization for Tech. Educ & Vocational Training
Riyadh
SAUDI ARABIA

Abstract

Three-phase controlled rectifiers have a wide range of applications, from small rectifier to large high voltage direct current (HVDC) transmission systems which are increasingly used throughout the world for long distance transmission and asynchronous interconnection. The transient performance of an HVDC power system is highly dependent on the parameters of the current/voltage regulators of the converter controls. This paper describes an alternative application of conventional bridge circuits using series connected bridges, of dissimilar rating, with different firing angles. Both steady-state and transient operations are presented. The experimental and analytical results are compared.

Key words: series bridges, dissimilar rating, transient response, control

1. Introduction

Phase-controlled thyristor converters have been widely used in AC-DC conversion applications were output voltage control is required. The static power converters are non-linear in nature, and consequently they generate harmonics into the supply. The generation of harmonics as well as several methods for harmonic reduction and power factor improvement is well explained in the existing literature [1-3].

An HVDC converter has normally a basic control system that controls the direct current in the rectifier and the extinction angle in the inverter. The basic control system is, however, the heart of the system, and to high degree it determines the operation properties of the whole HVDC plant. Although, there are a number of control schemes for AC-DC conversion to improve the power factor and reduce harmonics, the angle controlled scheme is still widely used in practical application. Several methods of control and transients have been reported in the literature [4-8].

Previous work [9-14] considered a modification to the three-phase bridge by additional by-pass thyristors which results in a decrease in the harmonic generation and the reactive volt-ampere absorption and the possibility of eliminating the on-load tap-changer on the converter transformer. The main contribution of this paper is the presentation of an alternative method of reducing both the harmonic generation and the reactive volt-ampere absorption by using series connected bridges, of dissimilar rating, with different firing angles.

Also in this paper, the laboratory model is developed to handle relatively small sudden changes of system voltage. Closed-loop control with proportional-plus-integral (PI) operation is used together with a filter in the feedback path, which can have a significant effect on system behavior. The system mathematical model was analyzed by a linear approximation using a discrete from implementation to study the theoretical response to sudden changes of system voltage for a bridge.

2. System description

In general, HVDC converters comprise pairs of three-phase with their transformers connected in Y/Y and Y/Δ to give an effective twelve-pulse scheme to eliminate the 5th, 7th, 17th and 19th harmonics, etc [15]. A reduction in both the harmonic content generated and the reactive volt-ampere absorption may be obtained by using differential firing of the thyristors in two series-connected bridges with dissimilar rating [16]. The smaller bridge operates at a variable firing angle α_1 to control the output DC voltage whilst the larger bridge has a fixed (small) value of α_2. Fig.1a shows the basic arrangement of a converter station with four series bridges. With negligible overlap angles the reduction in reactive volt-amperes with differential firing angle control is illustrated in Fig.1b for bridge ratings of 2:1. During abnormal system operating conditions the control of all the bridges can revert to the conventional mode with common firing angles.

2.1 *Laboratory model*

Half of the schematic shown in Fig.1a was represented by a laboratory model. For convenience, the bridge operating at a low value of firing angle α_2 was simply a diode bridge and a conventional thyristor bridge was used for the second bridge, as shown in Fig.2. When the AC supply voltage is large, the delay angle α_1 is increased beyond $90°$ to operate in the inverter mode, thus giving the required net value of DC output voltage. The transformer winding connections are considered to be similar for both corresponding primary and secondary sides. The feedback control loop system has a current transducer for measuring the DC current, a controller, a low-pass filter, an analogue to digital converter (ADC), and a firing pulse circuit for providing pulses to the bridge devices. The principle of operation is that a current error signal is generated and the bridge voltage is increased or decreased until the current error is reduced to an acceptable level. A current control loops with integral control and/or proportional integral (PI) operation is usually used in automatic systems. The measured current is compared with a reference current and the difference e(t) is applied to an amplifier to produce the firing angle error (Δα) at a rate proportional to the actuating error signal e(t). This change in firing angle (Δα) is added to the old firing angle to produce a new firing angle (modified angle) to the devices of the bridge circuit.

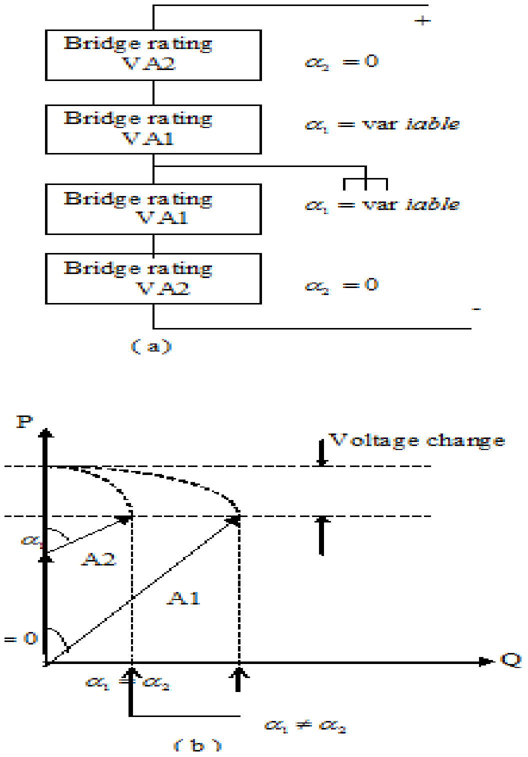

Fig.1: Characteristics of two bridges

a) Converter schematic
b) Operation of (A1 conventional, A2 sereies bridges)

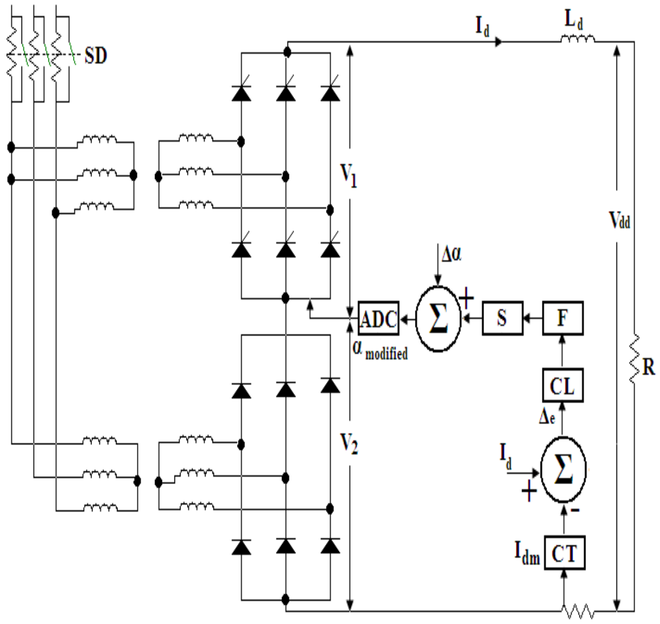

Fig.2: Laboratory scheme for series bridge connection circuit
CT - Current Transformer, CL- Controller, F – Filter, S - Analogue switch ,ADC - Analogue to Digital Converter, SD - 12% V_{LL}

2.2 *System mathematical model*

Several studies of a linearized mathematical model of a HVDC link have been reported in the literature [17-18]. This study considers a linearized mathematical model of the laboratory model to handle sudden changes of system voltage.

2.2.1 *Steady-state model*

The average value of the converter output DC voltage V_{dd} is composed of two components V_1 and V_2 :

$$V_{dd} = V_1 + V_2 \tag{1}$$

Where

$$V_1 = \frac{3\sqrt{2}V_{LL}T_{n1}}{\pi}\cos\alpha_1 - \frac{3}{\pi}I_d X_{c1} \tag{2}$$

$$V_2 = \frac{3\sqrt{2}V_{LL}T_{n2}}{\pi}\cos\alpha_2 - \frac{3}{\pi}I_d X_{c2} \tag{3}$$

$$\begin{aligned} V_{dd} = {} & \frac{3\sqrt{2}V_{LL}}{\pi}\left[T_{n2}\cos\alpha_2 + T_{n1}\cos\alpha_1\right] \\ & -\frac{3I_d}{\pi}\left[X_{c1} + X_{c2}\right] \end{aligned} \tag{4}$$

A suite of computer program was developed to determine the theoretical steady-state performance of the series bridge arrangement. Analysis of the supply current waveforms and the reactive volt-ampere absorption (VAR) are computed.

2.2.2 *Transient model*

A mathematical model based on linearized equations was developed and detailed investigations were carried-out for the dynamic behavior of the converter system. A small change in the thyristor firing angle delay $\Delta\alpha$ will cause a change in the DC output voltage ΔV_d, which will be added to the steady-state value of the DC output voltage. The effect of resistance and commutation reactance voltage drop is considered. The transient mathematical equation of the converter bridges is defined as follows:

The average value of the DC voltage for series connected bridges is given by:

$$V_{dd} = \frac{3\sqrt{2}V_{LL}}{\pi}\left[T_{n2} + T_{n1}\cos\alpha_1\right] - \frac{3I_d}{\pi}\left[X_{c1} + X_{c2}\right] \tag{5}$$

Consider a small variation occurs in the DC current equal to ΔI_d , a corresponding variation will be obtained in the delay firing angle $\Delta\alpha$ and in the DC output voltage ΔV_{dd} . Then

$$V_{ddnew} = V_{dd} + \Delta V_{dd} \tag{6}$$

$$I_{ddnew} = I_d + \Delta I_d \tag{7}$$

and $$\alpha_{new} = \alpha + \Delta\alpha \tag{8}$$

Then

$$V_{ddnew} = \frac{3\sqrt{2}V_{LL}}{\pi}\left[T_{n2} + T_{n1}\cos(\alpha_1 + \Delta\alpha_1)\right] - \frac{3}{\pi}\left[X_{c1} + X_{c2}\right]I_{dnew} \quad (9)$$

The sinusoidal function $\cos(\alpha_1 + \Delta\alpha_1)$ can be linearized, as

$$\cos(\alpha_1 + \Delta\alpha_1) = 1 - \frac{(\alpha_1 + \Delta\alpha_1)}{\pi/2} \quad (10)$$

Therefore

$$V_{ddnew} = \frac{3\sqrt{2}V_{LL}}{\pi}\left[T_{n2} + T_{n1}\right] - \frac{6\sqrt{2}V_{LL}}{\pi^2}T_{n1}(\alpha_1 + \Delta\alpha_1) - \frac{3}{\pi}\left[X_{c1} + X_{c2}\right]I_{dnew} \quad (11)$$

This can be simplified in the form

$$V_{ddnew} = V_{dh} + K_c(\alpha + \Delta\alpha) + K_{ci}I_{dnew} \quad (12)$$

Where

$$V_{dh} = \frac{3\sqrt{2}V_{LL}}{\pi}(T_{n1} + T_{n2})$$

$$K_c = \frac{-6\sqrt{2}V_{LL}}{\pi^2}T_{n1}$$

$$K_{c1} = \frac{-3}{\pi}(X_{c1} + X_{c2})$$

A computer program was written using discrete form implementation to study the theoretical response to sudden changes of system voltage for hybrid converter system used in this study.

2.3 *System transfer function*

Fig.3 shows the block diagram of the system model transfer function. The system comprises the same elements implemented in the closed-loop control model explained in [19], such as DC current transducer, current controller, first-order, low-pass filter and firing angle determination circuit. The measured current is compared with a reference current and the difference e(t) is applied to an amplifier to produce the firing angle error (Δα) at a rate proportional to the actuating error signal e(t). This change in firing angle (Δα) is added to the old firing angle to produce a new firing angle (modified angle) to the devices of the bridge circuit. For any small AC voltage change the current controller keeps near-constant current by controlling the firing-angle of the bridge devices. Large slow changes of AC voltage are handled by changing the transformer tap setting

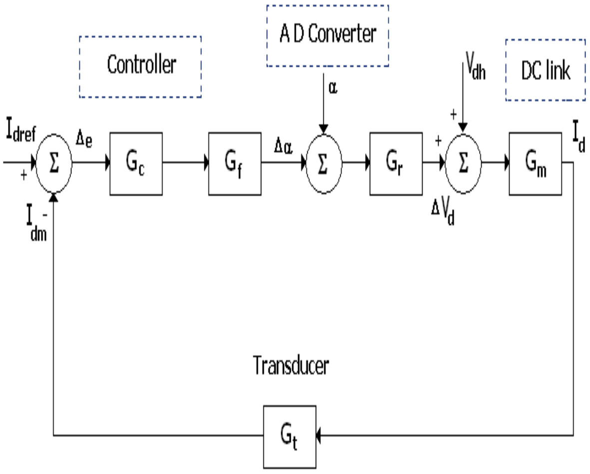

Fig.3: Block diagram of the series bridges converter and associated units

Consequently, the transfer functions of the blocks G_f, G_c and G_t are already defined in [19], while the transfer functions G_r and G_m for the series bridges are defined in Laplace form as follows:

$$G_r = \frac{K_c}{1 + Ts} \quad , \quad G_m = \frac{K_m}{1 + Ts} \quad (13)$$

Where

$$K_m = 1/R \quad , \quad T_m = L/R$$

And

$$R = R_L + R_d + 2(R_{W1} + R_{W2}) \quad ,$$
$$L = L_d + 2(L_{W1} + L_{W2})$$

The resistances R_{W1} and R_{W2} and inductances L_{W1} and L_{W2} for the converter transformer T_1 and T_2 respectively, are assumed to be equal in all phases. R_d And L_d are the resistance and inductance of the smoothing reactor, respectively. R_L is the converter load.

2.4 *Choice of controller parameters*

A trial and error approach is widely used [20], particularly in the process industries. It is based on the system behavior in the time domain in the form of transient and steady-state characteristics, when subjected to a unit step input signal of the DC current. The converter output DC current may be required to have no more than 15% overshoot and a steady-state error less than 2%. There is no fixed rule for this approach, although it is more common to adopt the following:

For the proportional-only controller is considered. The closed loop transfer function of the overall converter control system is determined, as indicated in the following equation:

$$f_1(s) = \frac{G_{(s)}}{1+G_{(s)}H(s)} = \frac{K_p K_f K_c K_m}{(1+sT_f)(1+sT)(1+sT_m)+K_p K_f K_c K_m} \qquad (14)$$

A step input signal is applied to the closed-loop transfer function of the converter with a P-type controller. Different responses of the DC output current are obtained, as shown in Fig.4, for different values of gain K_b, without any verification of the steady-state error. It can be seen that the oscillatory effect is increased as K_b is increased. Thus the adequate controller gain K_b is equal to 3 for an acceptable overshoot less than 15%.

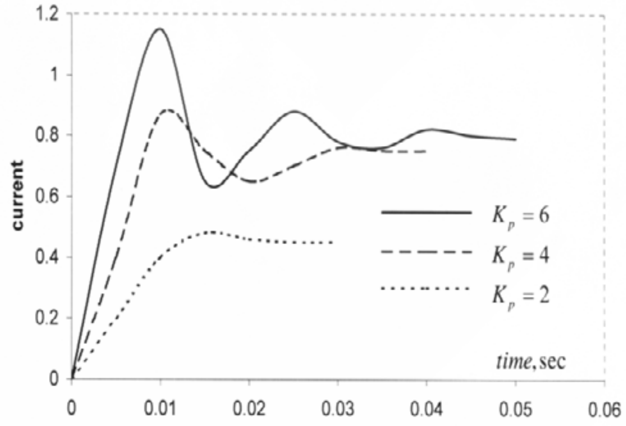

Fig.4: System transient influence of K_P

The closed-loop transfer function of the converter with a PI controller, keeping the determined value of K_b constant, is given by:

$$f_2(s) = \frac{K(s+b)}{s(1+sT_1)(1+sT)(1+sT_m)+k(s+b)} \qquad (15)$$

A step input signal is applied to this closed-loop transfer function $f_2(s)$, and different values of the controller integral time constant T_i are obtained to get the satisfactory steady-state error, as shown in Fig.5. The adequate T_i is determined to be equal to 5ms to get a fast response and steady-state error of about 2%.

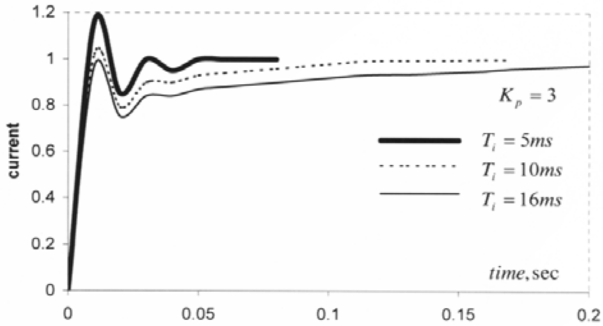

Fig.5: System transient response influence of K_P *and* T_i

3. Comparison of theoretical and experimental results

A rang of operating conditions was studies both theoretically and experimentally. Fig.6 shows the variation of DC voltage with firing angle α_1. Note that if α_1 is increased the voltage reduces, and if α_1 goes beyond $90°$, the controller bridge operates in the inverter mode. Fig.7 shows the computed and experimental results for the reactive power. Good agreement was obtained between the computed and measured values.

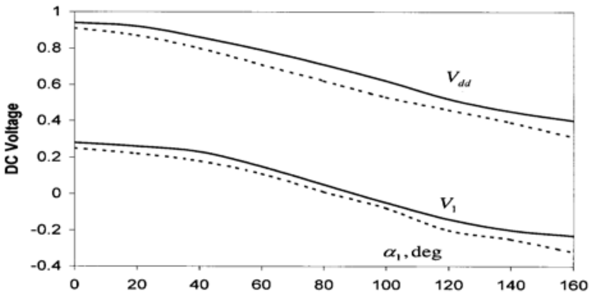

Fig.6: Output DC voltage characteristics
_______ Computed
- - - - - - - Measured

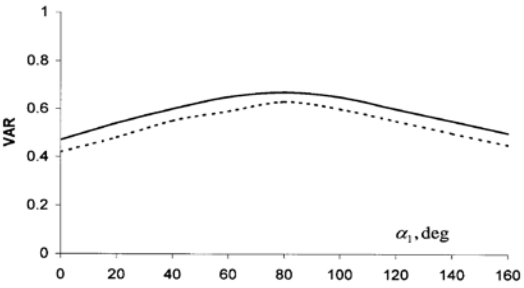

Fig.7: VAR Characteristics
_______ Computed
- - - - - - - Measured

The use of a PI controller leads to a fast response to step changes of system voltage. Therefore, in this study, representative results are shown for a sudden step-change of system voltage using a PI controller, with gain parameter K_b and time constant T_i. The system response was investigated by measuring the DC current and the firing angle α_1 of the Thyristor Bridge. An experimental trial-and-error technique was used to optimize the system response. In addition to the results obtained in previous section for optimizing controller parameters, satisfactory results were obtained from the laboratory model. To study the transient response of the system model, the line AC voltage setting was given a step-change increase of about 12%, as shown in Fig.8.

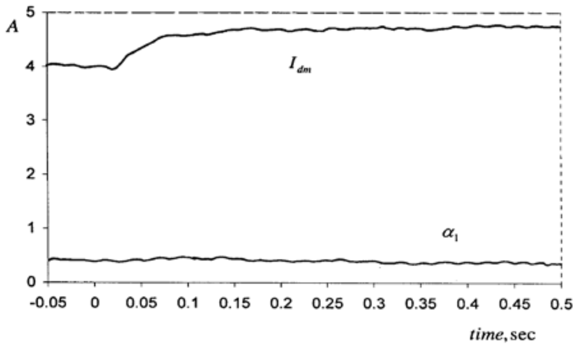

Fig.8: System response in the absence of feedback control

The system response for the same step-change is applied with a feedback control system of fixed gain equal to 4 and a different time constant T_i, as shown in Fig.9. It can be seen that with a higher time constant no overshoot occurs and the DC current changes smoothly, but the time taken is about 90ms. Reducing the gain for the same time constant T_i will gives less oscillation and the value of overshoot decreases, as shown in Fig.10a. Finally, an improvement in the response time has been obtained in Fig.10b. The setting time to reach a near steady-state value took about 70ms.

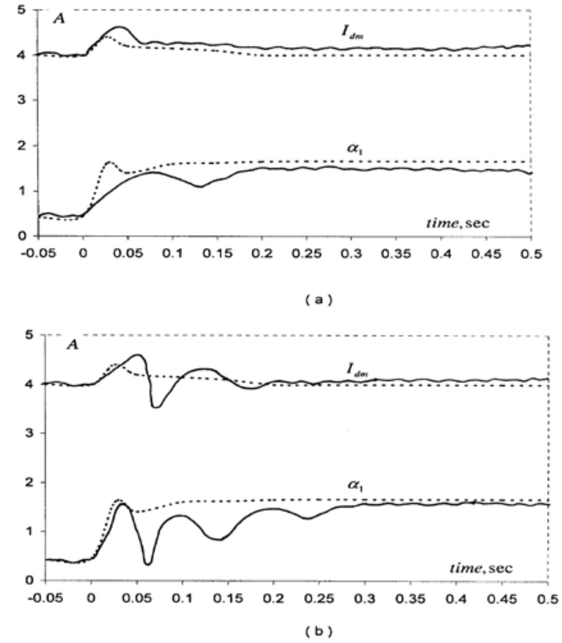

Fig.9: System response due to sudden change of system voltage
a) $K_P = 4$, $T_i = 16.5ms$ - - - Computed
b) $K_P = 4$, $T_i = 10ms$ ______ Measured

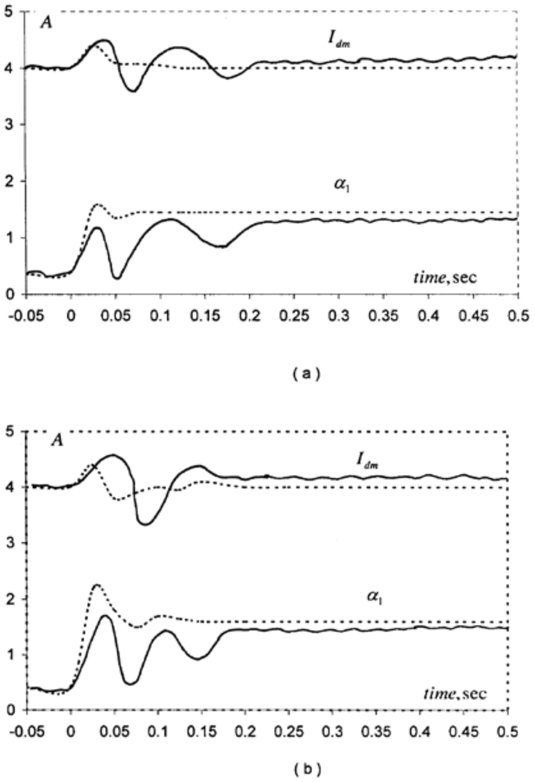

Fig.10: System response due to sudden change of system voltage

a) $K_P = 3$, $T_i = 10ms$ - - - - - Computed

b) $K_P = 3$, $T_i = 5ms$ ______ Measured

It can be concluded that the settling time to reach a near steady-state value is longer for those results obtained using a high value of controller time constant. A fast response time was achieved with a higher gain K_b , but the overshoot is noticeable.

3.1 *Response to a large disturbance*

The previous tests demonstrate the system response due to a sudden change of 12% of AC line voltage at the primary side of the converter transformer. The experimental investigation was extended to study the effect of rejecting the resistive load at the DC side. This test exposes the control to a large disturbance.

A rejection of about 40% of the resistive load was applied to the system without line fault protection, and the system behavior is presented in Fig.11. With a control system the response is very fast, activating the Thyristor Bridge by its firing angle delay α_1 , which drives the DC current to its reference value.

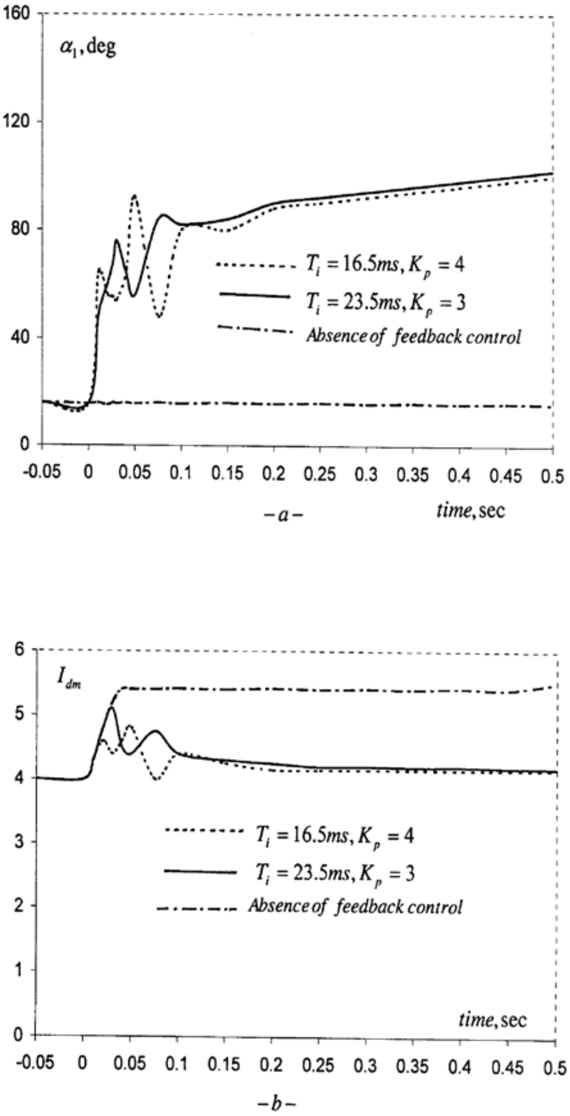

Fig.11: System response due to large sudden change of system voltage using PI control (experimental results)

a) α_1 b) I_{dm}

It can be seen that with a higher time constant and lower gain the steady-state response is good, but the transients take a longer time to settle down. The situation with a high gain setting and a lower time constant gives better steady-state response and the current reaches a near steady-state value in about 100ms.

The above scheme was only considered for the rectifier mode of operation. However, this control feature in the inverter mode of operation should provide similar improvements. One possibility would be to use the smaller bridge with fast-acting control of the angle of advance β_m to control the DC voltage, whilst the larger bridge operates at a lower value of (safe) extinction angle.

4. Conclusion

A converter comprising two series-connected bridges, with different firing angles and dissimilar bridge ratings was investigated. The larger bridge was operated with a fixed (small) value of firing angle α_2, whilst the second smaller bridge with a rating of 40% of the larger bridge was operated with a variable firing angle α_1. The transient and steady-state performances of the laboratory model were both examined. The series bridges of the laboratory model could handle sudden changes of system voltage of about $\pm 29\%$ by varying the switching angle α_1 of the smaller bridge. For transient operation a proportional plus integral control loop with a low-pass filter has been use. Controller parameters were optimized to give the best response. Variation of the feed-back parameters has a considerable effect on the system behavior and with PI control a fast time-response is achieved which effectively damped-out the oscillation in about 70ms. Also, It can be noted that:

1- The computed and experimental results were in good agreement and showed the general characteristics obtained using series bridges.

2- The reactive volt-ampere absorption was reduced compared with a conventional bridge arrangement.3- DC power can be controlled by variation of DC current setting.

Nomenclature

V_d = DC line voltage

V_{LL} = AC line voltage of primary winding

I_d = Direct current in HVDC line

I_{dm} = feedback signal of DC current

α_1 = Delay angle of Thyristor Bridge

α_2 = Delay angle of Diode Bridge

R_r = Rectifier side resistance

R_L = DC line resistance

R_{w1} = Converter transformer windings resistance of Thyristor Bridge

R_{w2} = Converter transformer windings resistance of Diode Bridge

R_d = Smoothing reactor resistance

L_{w1} = Converter transformer windings inductance of Thyristor Bridge

L_{w2} = Converter transformer windings inductance of Diode Bridge

L_d = Smoothing reactor inductance

X_{c1} = Secondary leakage reactance per phase for Thyristor Bridge

X_{c2} = Secondary leakage reactance per phase for Diode Bridge

T_{n1} = Transformation ratio of thyristor bridge transformer

T_{n2} = Transformation ratio of diode bridge transformer

K_p = Proportional gain

K_c = Current controller gain

K_f = Filter gain

K_m = Series bridge gain

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