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Two-stage Input-Output Feedback linearization controller for AC-AC converter-based SST

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***Abstract* - Classical transformers are the most important constituent of the power system and act as a passive interface between high voltage and low voltage systems. They have undesirable characteristics such as poor voltage regulation, large size/weight, sensitivity to harmonics, and poor power flow control. Solid-state Transformers (SSTs), are an emerging power electronics-based technology, sought to replace classical transformers after a century. SSTs are equivalent to a classical transformer with embedded desired functionalities. In this paper, three-phase AC-AC converter with capacitor at the DC-link is employed as power electronic interface in MV and LV side of the SST. Input-output feedback linearization (IOFL) controller is used to control the AC-AC based SST in two stages for controlling the external and internal states. AC-AC SST is linearized by the input-output feedback linearization technique where an internal dynamics is observed. IOFL is used to control the internal dynamics and second stage of the controller in the outer loop. Simulation studies are realized to confirm the applicability of IOFL controller and the control method.**

Index Terms – Input-Output Feedback Linearization, AC-AC Converter, Solid-State Transformers.

I. Introduction

AC-AC converters with capacitor at the DC-link can independently control the reactive power on both sides [1]. The capacitor at the DC-link allows bidirectional flow of power in the converter. These features make the AC-AC converter a perfect solution for building three-phase SSTs. One of the possible SSTs configuration based on the three-phase AC-AC converters is given in Fig. 1. In this configuration two AC-AC converters are used, one in the MV and other on the LV side to shape the current and voltage waveforms and control active and reactive power flows. In addition, galvanic isolation and voltage level conversion is done by a three-phase medium frequency transformer (MFT). These topologies can provide full-functionalities of the SST [2], [3], [4], and [5].

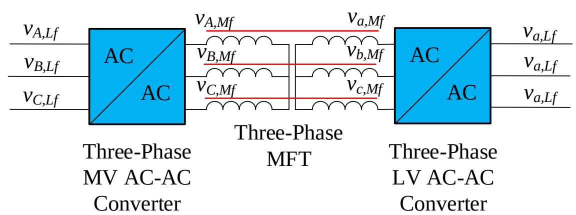

Fig. 1 SST based on three-phase AC-AC converter at MV and LV sides of the three-phase MFT.

Up to now many control techniques are used for AC-AC SSTs, they are emphasizing on the dynamic performance of the SST in the distribution grid. For instance, Ref. [6] proposes a controller structure based on linear quadratic regulator (LQR). This work is based on linear control theory and suffers from non-zero steady-state error and needs additional integral action to overcome the problem by sacrificing the dynamic performance of the converter.

Nonlinear control theory does not suffer from linear control theory problems. However, the design is highly depending on the plant under control. The application of the nonlinear control theory for controlling SSTs is reported in the papers [7], [8], [9], and [10]. Nonlinear control guaranties the asymptotic stability of the AC-AC SSTs regardless of their operating point based on the Lyapunov direct stability theory [7]. In addition, robust operation with different uncertainties can be achieved based on the sliding mode control is presented in [9] and [10]. However, no research articles discussed about the application of input-output feedback linearization (IOFL) control for AC-AC converters. This method is applied to three-phase AC-DC boost voltage source converters and three-phase UPS as presented in [11] and [12], respectively. Such papers have shown that IOFL control is an effective technique in controlling the power electronic systems. This technique provides the better stability feature as it involves with the nonlinear control theory. Also, the controller design is simpler.

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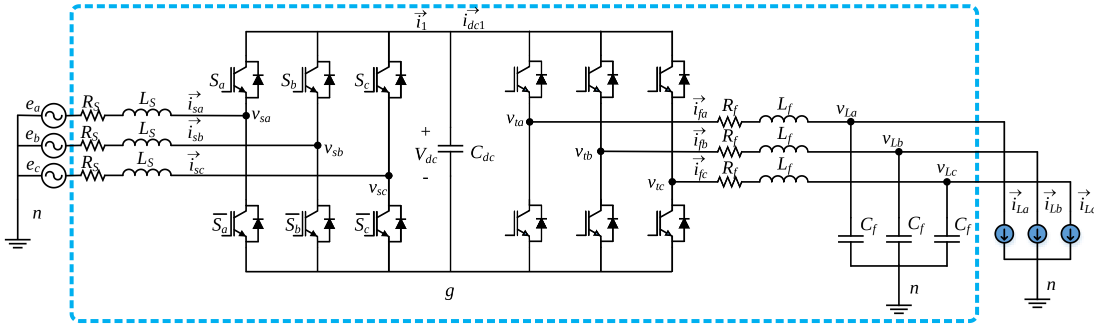

Fig. 2 Three-phase AC-AC converter at LV sides of the SST.

In this paper, a low frequency to medium frequency AC-AC converter is considered as the main building block of the SST on both MV and LV sides. In the medium frequency side of the AC-AC converter, power quality is not an issue, therefore, small series inductor can be used in the simulation of the controller, which is the leakage inductance of the MFT. IOFL is employed for linearizing the LV side AC-AC converter of the SST. The system zero dynamic is identified and controlled by an outer control loop such that the global asymptotic stability can be preserved. Simulation is done on a 400 V to 400 AC-AC converters with a DC-link voltage of 500 V which can be implemented based on the 1200 V standard semiconductor modules. The controller applicability is validated using simulation results in MATLAB/Simulink software.

II. SST Simplified Model

As can be seen in Fig. 2, MV and LV side AC-AC converters have the same topology. Thee describing differential equations of the AC-AC are extracted from [7]. For LV AC-AC converter, differential equations are presented in equations (1) to (7):

$$\frac{d}{dt}i_{sd} = -\frac{R_s}{L_s}i_{sd} + \omega_1 i_{sq} - \frac{v_{dc}}{2L_s}u_{1d} + \frac{1}{L_s}e_d \tag{1}$$

$$\frac{d}{dt}i_{sq} = -\omega_1 i_{sd} - \frac{R_s}{L_s}i_{sq} - \frac{v_{dc}}{2L_s}u_{1q} + \frac{1}{L_s}e_q \tag{2}$$

$$\frac{d}{dt}v_{dc} = \frac{3}{4C}\left(i_{sd}u_{1d} + i_{sq}u_{1q}\right) - \frac{3}{4C}\left(i_{fd}u_{2d} + i_{fq}u_{2q}\right) \tag{3}$$

$$\frac{d}{dt}i_{fd} = -\frac{R_f}{L_f}i_{fd} + \omega_2 i_{fq} + \frac{v_{dc}u_{2d}}{2L_f} - \frac{v_{Ld}}{L_f} \tag{4}$$

$$\frac{d}{dt}i_{fq} = -\frac{R_f}{L_f}i_{fq} - \omega_2 i_{fd} + \frac{v_{dc}u_{2q}}{2L_f} - \frac{v_{Lq}}{L_f} \tag{5}$$

$$\frac{d}{dt}v_{Ld} = \frac{1}{C_f}i_{fd} + \omega_2 v_{Lq} - \frac{1}{C_f}i_{Ld} \tag{6}$$

$$\frac{d}{dt}v_{Lq} = \frac{1}{C_f}i_{fq} - \omega_2 v_{Ld} - \frac{1}{C_f}i_{Lq} \tag{7}$$

Where v_{sd} and v_{sq} are the dq components of $\mathbf{v}_s$ and e_d and e_q are the dq components of $\mathbf{E}_s$ which is the MFT three-phase output voltage vector. Also, v_{td} and v_{tq} are the dq components of $\mathbf{v}_t$ and v_{Ld} and v_{Lq} are the dq components of $\mathbf{v}_L$ which is the load three-phase output voltage vector. For modelling of MV AC-AC converter, $\mathbf{v}_L$ can be replace by the grid voltage $\mathbf{v}_G$. i_{sd} and i_{sq} indicate the dq components $\mathbf{i}_s$. The three-phase load and inverter currents are symbolized by $\mathbf{i}_L$ (i_{Ld} and i_{Lq}) and $\mathbf{i}_f$ (i_{fd} and i_{fq}), respectively. L_s and R_s are the grid side filter and the equivalent resistance and inductance of the distribution network, respectively. Besides, R_f, L_f, and C_f are the components of load side filter.

III. Implementing Feedback-Linearization for SST

Equations (1) to (7) are the SST's simplified model differential equations. The system has 4-input and 4-output, so, it is a MIMO system. These equations can be rewritten in the following compact form as:

$$\begin{cases}\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}) + \mathbf{g}(\mathbf{x})\mathbf{u} \\ \mathbf{y} = \mathbf{h}(\mathbf{x})\end{cases} \tag{8}$$

Where;

$$\begin{aligned}\mathbf{x} &= \begin{bmatrix} i_{sd} & i_{sq} & v_{dc1} & i_{fd} & i_{fq} & v_{Ld} & v_{Lq}\end{bmatrix}^T \\ \mathbf{u} &= \begin{bmatrix} u_{1d} & u_{1q} & u_{2d} & u_{2q}\end{bmatrix}^T\end{aligned} \tag{9}$$

$$\mathbf{f}(\mathbf{x}) = \begin{bmatrix} -\frac{R_s}{L_s}i_{sd} + \omega_1 i_{sq} + \frac{1}{L_s}e_d \\ -\omega_1 i_{sd} - \frac{R_s}{L_s}i_{sq} + \frac{1}{L_s}e_q \\ 0 \\ -\frac{R_f}{L_f}i_{fd} + \omega_2 i_{fq} - \frac{v_{Ld}}{L_f} \\ -\frac{R_f}{L_f}i_{fq} - \omega_2 i_{fd} - \frac{v_{Lq}}{L_f} \\ \frac{1}{C_f}i_{fd} + \omega_2 v_{Lq} - \frac{1}{C_f}i_{Ld} \\ \frac{1}{C_f}i_{fq} - \omega_2 v_{Ld} - \frac{1}{C_f}i_{Lq} \end{bmatrix} \tag{10}$$

$$\mathbf{g}(\mathbf{x})=\begin{bmatrix} -\frac{v_{dc}}{2L_s} & 0 & \frac{3i_{sd}}{4C} & 0 & 0 & 0 & 0 \\ 0 & -\frac{v_{dc}}{2L_s} & \frac{3i_{sq}}{4C} & 0 & 0 & 0 & 0 \\ 0 & 0 & -\frac{3i_{fd}}{4C} & \frac{v_{dc}}{2L_f} & 0 & 0 & 0 \\ 0 & 0 & -\frac{3i_{fq}}{4C} & 0 & \frac{v_{dc}}{2L_f} & 0 & 0 \end{bmatrix}^T \quad (11)$$

$$\mathbf{y}=\mathbf{h}(\mathbf{x})=\begin{bmatrix} i_{sd} & i_{sq} & v_{Ld} & v_{Lq} \end{bmatrix}^T \quad (12)$$

The extraction of the control law can be initiated by deriving time derivative of the output vector in equation (12) as follows:

$$\begin{bmatrix} \dot{y}_1 \\ \dot{y}_2 \\ \dot{y}_3 \\ \dot{y}_4 \end{bmatrix}=\frac{d}{dt}\begin{bmatrix} i_{sd} \\ i_{sq} \\ v_{Ld} \\ v_{Lq} \end{bmatrix}=\begin{bmatrix} -\frac{R_s}{L_s}i_{sd}+\omega_1 i_{sq}-\frac{v_{dc}}{2L_s}u_{1d}+\frac{1}{L_s}e_d \\ -\omega_1 i_{sd}-\frac{R_s}{L_s}i_{sq}-\frac{v_{dc}}{2L_s}u_{1q} \\ \frac{1}{C_f}i_{fd}+\omega_2 v_{Lq}-\frac{1}{C_f}i_{Ld} \\ \frac{1}{C_f}i_{fq}-\omega_2 v_{Ld}-\frac{1}{C_f}i_{Lq} \end{bmatrix} \quad (13)$$

The inputs (u_{1d} and u_{1q}) are observed in i_{sd} and i_{sq} time derivatives, so, there is no need for continuing time derivatives. But, second time derivatives of v_{Ld} and v_{Lq} are required. Final time derivative of output vector is given in (14) at the bottom of this page. The following control low cancels nonlinear nature of the system from the view point of the new input control **v**.

$$\mathbf{u}=\mathbf{E}^{-1}(\boldsymbol{\upsilon}-\mathbf{W}) \quad (15)$$

Where;

$$\boldsymbol{\upsilon}=\begin{bmatrix} \upsilon_1 & \upsilon_2 & \upsilon_3 & \upsilon_4 \end{bmatrix} \quad (16)$$

$$\det(\mathbf{E})=\left(-\frac{v_{dc}}{2L_s}\right)\left(-\frac{v_{dc}}{2L_s}\right)\left(\frac{v_{dc}}{2C_f L_f}\right)\left(\frac{v_{dc}}{2C_f L_f}\right) \quad (17)$$

$$\mathbf{E}^{-1}=\begin{bmatrix} -\frac{2L_s}{v_{dc}} & 0 & 0 & 0 \\ 0 & -\frac{2L_s}{v_{dc}} & 0 & 0 \\ 0 & 0 & \frac{2C_f L_f}{v_{dc}} & 0 \\ 0 & 0 & 0 & \frac{2C_f L_f}{v_{dc}} \end{bmatrix} \quad (18)$$

From equations (17) and (18), the condition for existing inverse of **E** is $v_{dc}\neq 0$ that is always held. Substituting (15) into (14) yields a new set of deferential equations as:

$$\begin{bmatrix} \dot{y}_1 \\ \dot{y}_2 \\ \ddot{y}_3 \\ \ddot{y}_4 \end{bmatrix}=\boldsymbol{\upsilon} \text{ or } \begin{bmatrix} \dot{y}_1 \\ \dot{y}_2 \\ \dot{y}_3 \\ \dot{y}_4 \\ \dot{y}_5 \\ \dot{y}_6 \end{bmatrix}=\begin{bmatrix} 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \\ 0&0&0&0&1&0 \\ 0&0&0&0&0&1 \\ 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \end{bmatrix}\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \\ y_5 \\ y_6 \end{bmatrix}+\begin{bmatrix} \upsilon_1 \\ \upsilon_2 \\ 0 \\ 0 \\ \upsilon_3 \\ \upsilon_4 \end{bmatrix} \quad (19)$$

The order of the new differential equations is 6, while the order of the original system is 7. Therefore, the system has one internal dynamic. The control and stability of the internal dynamic will be discussed in the next section. As the new system is linear, any design methodology based on the linear control theory can be used.

In a tracking problem, errors of the under control signals can be represented as follows:

$$\mathbf{e}=\mathbf{y}-\mathbf{y_d} \quad (20)$$

Their first time derivatives are

$$\begin{aligned} \dot{e}_1 &= \dot{y}_1-\dot{y}_{1d} \\ \dot{e}_e &= \dot{y}_2-\dot{y}_{2d} \\ \dot{e}_3 &= \dot{y}_3-\dot{y}_{3d} \\ \dot{e}_4 &= \dot{y}_4-\dot{y}_{4d} \end{aligned} \quad (21)$$

The second time derivatives are:

$$\begin{aligned} \ddot{e}_3 &= \ddot{y}_3-\ddot{y}_{3d} \\ \ddot{e}_4 &= \ddot{y}_4-\ddot{y}_{4d} \end{aligned} \quad (22)$$

New control laws can be defined as follows:

$$\begin{bmatrix} \dot{y}_1 \\ \dot{y}_2 \\ \ddot{y}_3 \\ \ddot{y}_4 \end{bmatrix}=\mathbf{W}+\mathbf{E}\mathbf{u}=\begin{bmatrix} -\frac{R_s}{L_s}i_{sd}+\omega_1 i_{sq}+\frac{1}{L_s}e_d \\ -\omega_1 i_{sd}-\frac{R_s}{L_s}i_{sq} \\ -\frac{R_f}{C_f L_f}i_{fd}+\frac{2\omega_2}{C_f}i_{fq}-\frac{v_{Ld}}{C_f L_f}-\omega_2^2 v_{Ld}-\frac{\omega_2}{C_f}i_{Lq}-\frac{1}{C_f}\frac{d}{dt}i_{Ld} \\ -\frac{R_f}{C_f L_f}i_{fq}-\frac{2\omega_2}{C_f}i_{fd}-\frac{v_{Lq}}{C_f L_f}-\omega_2^2 v_{Lq}+\frac{\omega_2}{C_f}i_{Ld}-\frac{1}{C_f}\frac{d}{dt}i_{Lq} \end{bmatrix}+\begin{bmatrix} -\frac{v_{dc}}{2L_s} & 0 & 0 & 0 \\ 0 & -\frac{v_{dc}}{2L_s} & 0 & 0 \\ 0 & 0 & \frac{v_{dc}}{2C_f L_f} & 0 \\ 0 & 0 & 0 & \frac{v_{dc}}{2C_f L_f} \end{bmatrix}\mathbf{u} \quad (14)$$

$$\begin{aligned}
\nu_1 &= \dot{y}_{1d} - k_{11}e_1 = \dot{y}_{1d} - k_{11}\left(y_1 - y_{1d}\right) \\
\nu_2 &= \dot{y}_{2d} - k_{21}e_2 = \dot{y}_{2d} - k_{21}\left(y_2 - y_{2d}\right) \\
\nu_3 &= \ddot{y}_{3d} - k_{32}\dot{e}_3 - k_{31}e_3 \\
&= \ddot{y}_{3d} - k_{32}\left(\dot{y}_3 - \dot{y}_{3d}\right) - k_{31}\left(y_3 - y_{3d}\right) \\
\nu_4 &= \ddot{y}_{4d} - k_{42}\dot{e}_4 - k_{41}e_4 \\
&= \ddot{y}_{4d} - k_{42}\left(\dot{y}_4 - \dot{y}_{4d}\right) - k_{41}\left(y_4 - y_{4d}\right)
\end{aligned} \quad (23)$$

Substituting (23) into (19) gives and then applying Laplace transform:

$$\begin{aligned}
s + k_{11} &= 0 \\
s + k_{21} &= 0 \\
s^2 + k_{32}s + k_{31} &= 0 \\
s^2 + k_{42}s + k_{41} &= 0
\end{aligned} \quad (24)$$

Selecting k_{ij}>0 result in a stable system where errors approach zero when time approaches infinity. Therefore, designing of the controller reduces to the selection of k_{ij} in the domain of positive real numbers. The control law can be rewritten using the system state variables:

$$\begin{aligned}
\upsilon_1 &= \dot{I}_{sq} - k_{11}\left(i_{sq} - I_{sq}\right) \\
\upsilon_2 &= \dot{I}_{sq} - k_{21}\left(i_{sq} - I_{sq}\right) \\
\upsilon_3 &= \ddot{V}_{Ld} - k_{32}\left(\dot{v}_{Ld} - \dot{V}_{Ld}\right) - k_{31}\left(v_{Ld} - V_{Ld}\right) \\
\upsilon_4 &= \ddot{V}_{Lq} - k_{42}\left(\dot{v}_{Lq} - \dot{V}_{Lq}\right) - k_{41}\left(v_{Lq} - V_{Lq}\right)
\end{aligned} \quad (25)$$

Final control law of the input-output feedback linearization is obtained by simplifying equation (25) and are presented in equations (26) to (29) at the bottom of this page.

IV. Stabilize Internal Dynamics

Equation (27) is the only internal dynamic of the system.

$$\frac{d}{dt}v_{dc} = \frac{3}{4C}\left(i_{sd}u_{1d} + i_{sq}u_{1q}\right) - \frac{3}{4C}\left(i_{fd}u_{2d} + i_{fq}u_{2q}\right) \quad (30)$$

Based on the steady-state analysis of the SST given in [7], the power balance equation in first stage of converter is:

$$\frac{3}{2}\left\{E_m I_{sd} - R_s I_{sd}^2 - R_s I_{sq}^2\right\} = v_{dc} i_{dc1} \quad (31)$$

Also, second stage of converter equivalent resistance from the view point of i_{dc2} is:

$$R_{eq} = \frac{v_{dc}}{i_{dc2}} = \frac{V_{dc}}{I_{dc2}} \rightarrow G_{eq} = \frac{1}{R_{eq}} \quad (32)$$

This equivalent resistance in the steady-state can be calculated as:

$$G_{eq} = \frac{2}{\left(V_{dc}\right)^2}\begin{pmatrix} -R_f C_f{}^2 \omega_2^2 V_{Lq}{}^2 + R_f C_f{}^2 \omega_2^2 V_{Ld}{}^2 \\ -2R_f C_f \omega_2 I_{Ld} V_{Lq} + 2R_f C_f \omega_2 I_{Lq} V_{Ld} \\ +I_{Ld}V_{Ld} + I_{Lq}V_{Lq} + R_f I_{Lq}{}^2 + R_f I_{Ld}{}^2 \end{pmatrix} \quad (33)$$

Where; load current component can be obtained from the output voltage and the connected power as follows:

$$I_{Ld} = \frac{V_{Ld}P_L + V_{Lq}Q_L}{V_{Ld}^2 + V_{Lq}^2}, I_{Lq} = \frac{V_{Lq}P_L - V_{Ld}Q_L}{V_{Ld}^2 + V_{Lq}^2} \quad (34)$$

So, by substituting (32) and (33) in (31):

$$\frac{d}{dt}v_{dc} = \frac{3}{2v_{dc}C}\left\{E_m I_{sd} - R_s I_{sd}^2 - R_s I_{sq}^2\right\} - \frac{3G_{eq}}{4C}v_{dc} \quad (35)$$

Where I_{sd} is selected as the control input of equation (36) and also unity power factor is assumed I_{sq}=0. Now, new state variable is defined as $\zeta = v_{dc}^2$ and so (35) becomes:

$$\frac{d}{dt}\zeta = \frac{3}{C}\left\{E_m I_{sd} - R_s I_{sd}^2\right\} - \frac{3G_{eq}}{2C}\zeta \quad (36)$$

Therefore, following IOFL linearizes equation (36) as:

$$u_V = \upsilon_V + \frac{3G_{eq}}{2C}\zeta \rightarrow \frac{d}{dt}\zeta = \upsilon_V \quad (37)$$

So, any linear control theory can be used to control (37). One selection is:

$$\upsilon_V = \frac{d}{dt}\zeta_{ref} - k_V\left(\zeta - \zeta_{ref}\right) \quad (38)$$

$$u_{1d} = -\frac{v_{dc}}{2L_s}\left\{\dot{I}_{sd} - k_{11}\left(i_{sd} - I_{sd}\right) + \frac{R_s}{L_s}i_{sd} - \omega_1 i_{sq} - \frac{1}{L_s}e_d\right\} \quad (26)$$

$$u_{1q} = -\frac{2L_s}{v_{dc}}\left\{\dot{I}_{sq} - k_{21}\left(i_{sq} - I_{sq}\right) + \omega_2 i_{sd} + \frac{R_s}{L_s}i_{sq}\right\} \quad (27)$$

$$u_{2d} = \frac{2C_f L_f}{v_{dc}}\left\{\ddot{V}_{Ld} - k_{32}\left(\dot{v}_{Ld} - \dot{V}_{Ld}\right) - k_{31}\left(v_{Ld} - V_{Ld}\right) + \frac{R_f}{C_f L_f}i_{fd} - \frac{2\omega_2}{C_f}i_{fq} + \frac{v_{Ld}}{C_f L_f} + \omega_2^2 v_{Ld} + \frac{\omega_2}{C_f}i_{Lq} + \frac{1}{C_f}\frac{d}{dt}i_{Ld}\right\} \quad (28)$$

$$u_{2q} = \frac{2C_f L_f}{v_{dc}}\left\{\ddot{V}_{Lq} - k_{42}\left(\dot{v}_{Lq} - \dot{V}_{Lq}\right) - k_{41}\left(v_{Lq} - V_{Lq}\right) + \frac{R_f}{C_f L_f}i_{fq} + \frac{2\omega_2}{C_f}i_{fd} + \frac{v_{Lq}}{C_f L_f} + \omega_2^2 v_{Lq} - \frac{\omega_2}{C_f}i_{Ld} + \frac{1}{C_f}\frac{d}{dt}i_{Lq}\right\} \quad (29)$$

So, I_{sd} can be calculated from the quadratic equation (39). It can be considered as the control law of the second stage of the controller and it is given in equation (40) at the bottom of previous page.

$$\frac{3}{C}\left\{E_m I_{sd} - R_s I_{sd}^2\right\} = \frac{d}{dt}\zeta_{ref} - k_V\left(\zeta - \zeta_{ref}\right) + \frac{3G_{eq}}{2C}\zeta \quad (39)$$

This controller can be considered for the MV side AC-AC converter due to the symmetry of the SST topology.

V. Simulation Results

The AC-AC SST simplified model defined in equations (1) to (7) along with feedback linearization control equations (26) to (29) and (38) are implemented in MATLAB/Simulink platform.

To overcome the non-zero steady-state error in DC voltage, an integral action is added to the control law in equation (38). The electrical parameters of three-phase AC-AC converter are given in table I.

TABLE I

AC-AC Converter Design Results

MFT Side Converter		Load Side Converter	
f_1	20 kHz	f_2	50 Hz
L_s	25 µH	L_f	5 mH
R_s	1 Ω	C_f	500 µF
C	1000 µF	R_f	0.2 Ω
k_{11}	10	k_{31}	2000
k_{21}	600	k_{32}	60
k_V	0.001	k_{41}	10
k_{VI}	0.04	k_{42}	60
E (peak)	163 V	$V_{L,phase}$ (RMS)	220 V
v_{dc}	500 V	P_L	2200 W
I_{sq}	0 A	Q_L	0 VAr

Simulation results are shown for 2 seconds in which four disturbances are applied to the plant for testing the behaviour of the proposed controller. The disturbances are: a 30% symmetrical voltage dip in the medium frequency input voltage at time 0.25 to 0.5 seconds, decreasing load by step change from 2200 W to zero at time 1 sec, and reversing the power flow from zero to -2200 W at time 1.5 second.

$$I_{sd} = \frac{E_m}{2R_s} \pm \frac{1}{2}\sqrt{1 - \frac{4C}{3R_s}\left\{\frac{d}{dt}\zeta_{ref} - k_V\left(\zeta - \zeta_{ref}\right) + \frac{3G_{eq}}{2C}\zeta\right\}} \quad (40)$$

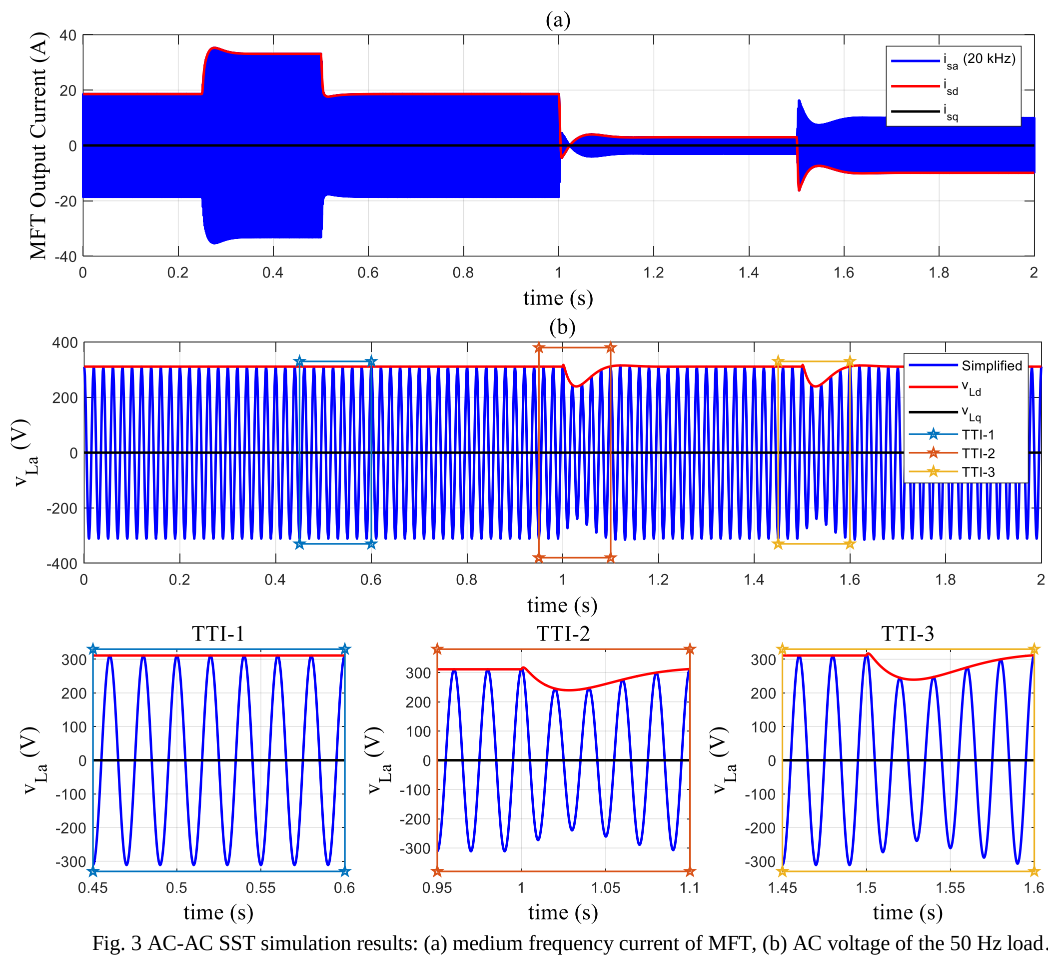

Fig. 3 AC-AC SST simulation results: (a) medium frequency current of MFT, (b) AC voltage of the 50 Hz load.

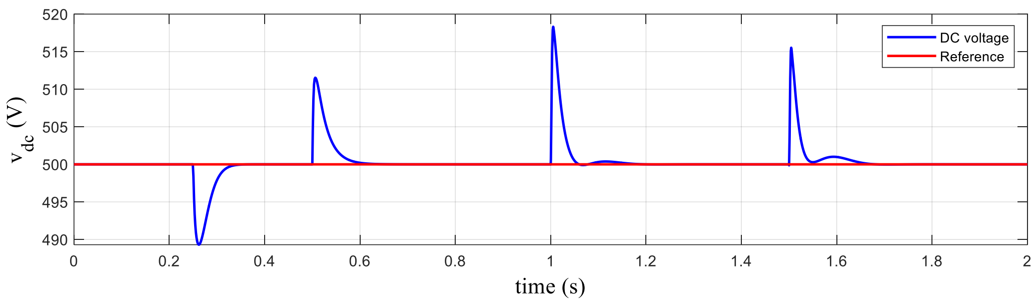

Fig. 4 DC voltage of the DC-link capacitor.

Fig. 3 (a) shows medium frequency current in the LV side of the MFT which flows into the AC-AC converter. Current is changing proportional to load side power, current increases when voltage decreases and it reverses when power flow reverses. Fig. 3 (b) indicates the load voltage variation versus various disturbances. It can be seen that the 30% voltage dip in the medium frequency voltage has no effect on the 50 Hz load voltage. Also, severe interruption in the load doesn't affect the voltage quality, significantly. Load voltage is magnified in three-time intervals TTI-1, TTI-2 and TTI-3 for better visualization and shown in Fig.3 (b). DC-link voltage response to the mentioned disturbances is presented in Fig. 4. Its maximum overshoot/undershoot in the voltage dip and load change are 12 V and 19 V which are 2.4% and 3.8% of the nominal DC voltage, respectively. Also, settling time is 0.1 and 0.05 second for voltage dip and severe load change responses, respectively.

The obtained results demonstrated that the proposed IOFL controller is applicable to AC-AC converter of the SST topology shown in Fig. 1. The controller guarantees the global stability of the system and also dynamic characteristic are promising. Therefore, IOFL can be considered as a solution in the AC-AC SST applications.

V. Conclusion

Applicability of the IOFL control method is validated for AC-AC converter with capacitive energy storage device in the DC-link. In solid-state transformers (SSTs), low frequency power can be converted into medium frequency power by AC-AC converters for enabling medium frequency transformer (MFT) usage. IOFL method is applied to AC-AC converters in two stages for controlling both external and internal states. Three-phase AC-AC converter has 7 states where 6 of them are external and the other is the internal state which is controlled by an outer control loop over the first stage IOFL. The controller benefits from both advantages of the linear and nonlinear control theories. In one hand, global asymptotic stability is achieved and on the other hand, linear control theory methods such as proportional and integral controllers are adopted for simplicity. The designed controller is validated using simulations on a 2.2 kW 400 V AC-AC converter as the LV side converter of an SST.

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