

COMPREHENSIVE AND ASYMPTOTIC STABLE CONTROLLER FOR SST-BASED MICRO-GRIDS

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ABSTRACT

Solid-State Transformers are one of the most complicated power electronic devices that are sought to be an alternative for conventional low frequency distribution transformers (LFDTs) with embedded functionalities. Active power injection at MVDC and LVDC ports of the SST can affect the stability of the controller, drastically. In this paper, a control method based on the Lyapunov Direct Theory (LDT) is presented for the SST-based MGs. Simulations are performed using MATLAB/Simulink for constant and variable power injection at MVDC and LVDC ports of the SST as well LVAC side. Simulation results show that the proposed controller guarantees the global and asymptotic stability features of the SST-based MGs subject to internal stability of the connected subsystems.

INTRODUCTION

Solid-State Transformer's (SST) power conversion stages provide energy hubs at Medium Voltage DC (MVDC), Low Voltage DC (LVDC) and Low Voltage AC (LVAC) levels. This key feature makes the SSTs an optimal solution for integrating both AC and DC Micro-Grids (MGs) into distribution systems.

Four main issues efficiency, cost, competition, and protection compatibility are challenging SSTs vs LFDTs and therefore SSTs can't be a regular replacement for LFDTs in the near foreseeable future [1]. The authors of [2] disclose and explain the roadmap of the future renewable electric energy delivery and management (FREEDM) system in which a plug-and-play placing method for the distributed resources is desired where the key for managing the energy at AC/DC and MV/LV is SST. Finally, the smart transformer idea directly uses the SSTs as the core of micro-grids (MGs) in the HEART project as shown in Fig. 1 [3].

As an accepted solution for interfacing renewable energy resources into the distribution grids, there are several works in the literature that addressing the SST based MG issues. In [4], a model that provides a framework for small-signal stability assessment of SST is developed. The model considers the capability of plug-and-play support of dc loads/generations. However, this work doesn't reflect the stability properties for an arbitrary power injection from DC subsystems.

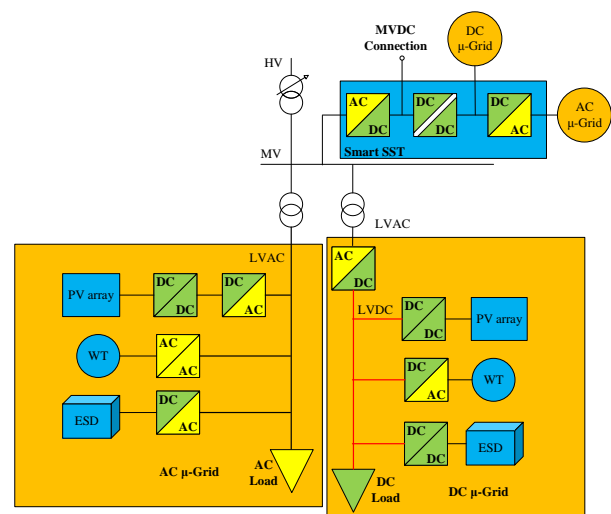


Fig. 1 comparing the independent AC and DC MGs vs SST-based MGs [3].

Power management characteristics of SST based MGs has been discussed in [5] where stability of the system is addressed based on the conventional techniques in the linear control theory and it doesn't discuss the asymptotic stability features of the nonlinear system. Authors of [6] have presented the control architecture of the SST based MGs based on the high frequency commercially available devices but they haven't addressed the stability features for an arbitrary plug-and-play dc load or power resource. More detailed work is presented in [7] where integration of SST and zonal DC MGs has been investigated. An intelligent energy management system has been proposed to handle power between multiple energy storages and resources. Hierarchy of the power management for SST based MGs at system level is the topic of [8]. Control strategies at different levels have been studied and it is shown that the SST is an effective solution for power management of MGs. However, these works only concentrate on the applicability of the idea and they haven't addressed the stability issues of the overall system with embedded subsystems with unpredictable power injection.

In this paper, an asymptotically stable controller is designed for SSTs based on the Lyapunov direct stability theory which guarantees plug-and-play of internally stable subsystems to SSTs for making MGs without violating the asymptotic stability of the SST based MGs.

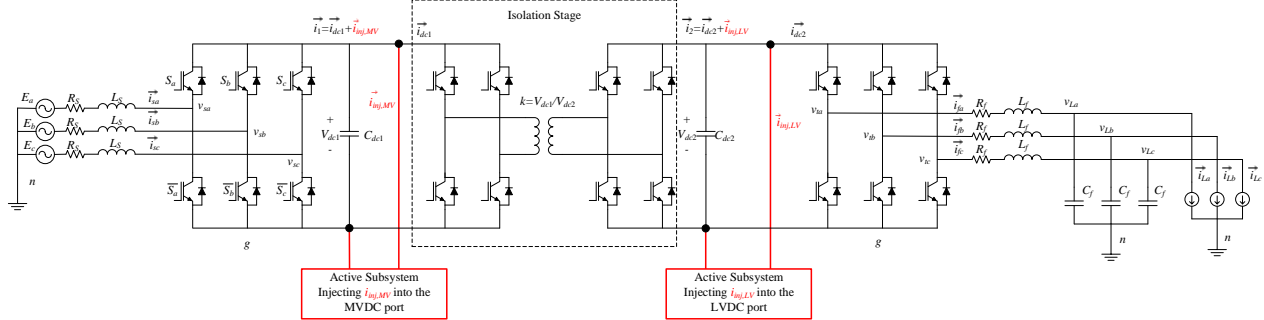


Fig. 2 Structure of a SST with arbitrary embedded energy ports.

MULTI-PORT SST MODEL

Fig. 3. Shows the SST topology used in this study. The overall differential equations of the SST without embedded active powers are given in [9]. The SST differential equations with embedded current injections can be represented as follows:

$$\frac{d}{dt} i_{sd} = -\frac{R_s}{L_s} i_{sd} + \omega i_{sq} - \frac{v_{dc1}}{2L_s} u_{1d} + \frac{1}{L_s} e_d \quad (1)$$

$$\frac{d}{dt} i_{sq} = -\omega i_{sd} - \frac{R_s}{L_s} i_{sq} - \frac{v_{dc1}}{2L_s} u_{1q} + \frac{1}{L_s} e_q \quad (2)$$

$$\frac{d}{dt} v_{dc1} = \frac{3}{4C} (i_{sd} u_{1d} + i_{sq} u_{1q}) - \frac{3}{4kC} (i_{fd} u_{2d} + i_{fq} u_{2q}) - \left(i_{inj,MV} + \frac{1}{k} i_{inj,LV} \right) \quad (3)$$

$$\frac{d}{dt} i_{fd} = -\frac{R_f}{L_f} i_{fd} + \omega i_{fq} + \frac{v_{dc2} u_{2d}}{2L_f} - \frac{v_{Ld}}{L_f} \quad (4)$$

$$\frac{d}{dt} i_{fq} = -\frac{R_f}{L_f} i_{fq} - \omega i_{fd} + \frac{v_{dc2} u_{2q}}{2L_f} - \frac{v_{Lq}}{L_f} \quad (5)$$

$$\frac{d}{dt} v_{Ld} = \frac{1}{C_f} i_{fd} + \omega v_{Lq} - \frac{1}{C_f} i_{Ld} \quad (6)$$

$$\frac{d}{dt} v_{Lq} = \frac{1}{C_f} i_{fq} - \omega v_{Ld} - \frac{1}{C_f} i_{Lq} \quad (7)$$

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 . Also, v_{1d} and v_{1q} are the dq components of \mathbf{v}_1 and v_{Ld} and v_{Lq} are the dq components of \mathbf{v}_L . i_{sd} and i_{sq} indicate the dq components \mathbf{i}_s , \mathbf{i}_f (i_{fd} and i_{fq}) and \mathbf{i}_L (i_{Ld} and i_{Lq}) are the inverter and load three-phase currents, respectively. R_s and L_s are the equivalent resistance and inductance of the distribution network and the grid side filter, respectively. In addition, R_f , L_f and C_f are the resistance, inductance and capacitance of the load side filter. The injected current at MV and LV DC ports are respectively represented by $i_{inj,MV}$ and $i_{inj,LV}$ and are shown in red color in equation (3).

In this model, isolation stage dynamics are neglected due to its fast dynamic response comparing the AC/DC and DC/AC stages. In addition, high frequency effects in the system are omitted and the model can be named simplified SST model. Port powers are identified based

on their arbitrary current injection into the MVDC and LVDC ports of the SST.

STEADY-STATE ANALYSIS

Steady-state analysis is essential for finding the stable operating regions of the SST. To simplify analysis, all the steady-state are denoted in uppercase letters and the most important equations at steady-state are given in the following equations:

$$U_{1d} = \frac{2}{V_{dc1}} \left[-R_s I_{sd} + \omega L_s I_{sq} + E_m \right] \quad (8)$$

$$U_{1q} = \frac{2}{V_{dc1}} \left[-\omega L_s I_{sd} - R_s I_{sq} \right] \quad (9)$$

$$U_{2d} = \frac{2}{V_{dc2}} \left[-R_f C_f \omega V_{Lq} + R_f I_{Ld} + (1 - L_f C_f \omega^2) V_{Ld} - L_f \omega I_{Lq} \right] \quad (10)$$

$$U_{2q} = \frac{2}{V_{dc2}} \left[R_f C_f \omega V_{Ld} + R_f I_{Lq} + (1 - L_f C_f \omega^2) V_{Lq} + L_f \omega I_{Ld} \right] \quad (11)$$

$$I_{dc2} = \frac{2}{V_{dc2}} \left(\begin{array}{l} -R_f C_f^2 \omega^2 V_{Lq}^2 + R_f C_f^2 \omega^2 V_{Ld}^2 \\ -2R_f C_f \omega I_{Ld} V_{Lq} + 2R_f C_f \omega I_{Lq} V_{Ld} \\ + I_{Ld} V_{Ld} + I_{Lq} V_{Lq} \\ + R_f I_{Lq}^2 + R_f I_{Ld}^2 \end{array} \right) \quad (12)$$

More details are given in [9]. From (3), the operating limits of the SST under connected active (or passive) subsystems can be estimated as:

$$-R_s I_{sd}^2 + E_m I_{sd} - R_s I_{sq}^2 - \left(\frac{I_{dc2}}{k} + I_{MV} + \frac{1}{k} I_{LV} \right) \frac{V_{dc1}}{2} = 0 \quad (13)$$

Where I_{MV} and I_{LV} are the steady-state values of the $i_{inj,MV}$ and $i_{inj,LV}$, respectively. This quadratic polynomial equation has solutions for I_{sd} in real numbers subject to

$$I_{dc2} \leq \frac{k}{2R_s V_{dc1}} \left(E_m^2 + 4R_s^2 I_{sq}^2 \right) - k \left(I_{MV} + \frac{1}{k} I_{LV} \right) \quad (14)$$

By replacing I_{dc2} from (12) into (14), following circle is obtained.

$$\begin{aligned}
 & \left[I_{Ld} + \frac{1}{2} \left(\frac{V_{Ld}}{R_f} - 2C_f \omega V_{Lq} \right) \right]^2 \\
 & + \left[I_{Lq} + \frac{1}{2} \left(\frac{V_{Lq}}{R_f} + 2C_f \omega V_{Ld} \right) \right]^2 \\
 & \leq \frac{1}{4R_s R_f} (E_m^2 - 4R_s^2 I_{sq}^2) - k \left(I_{MV} + \frac{1}{k} I_{LV} \right) \\
 & + 2C_f^2 \omega^2 V_{Lq}^2 + \frac{1}{4R_f^2} (V_{Ld}^2 + V_{Lq}^2)
 \end{aligned} \quad (15)$$

This circle is illustrated in Fig. 3 for different values of power injection into the grid. Generally, passive current (i.e. loads) reduce the acceptable region for lading the SST and active current injections at DC ports enhance the SST's acceptable operating region.

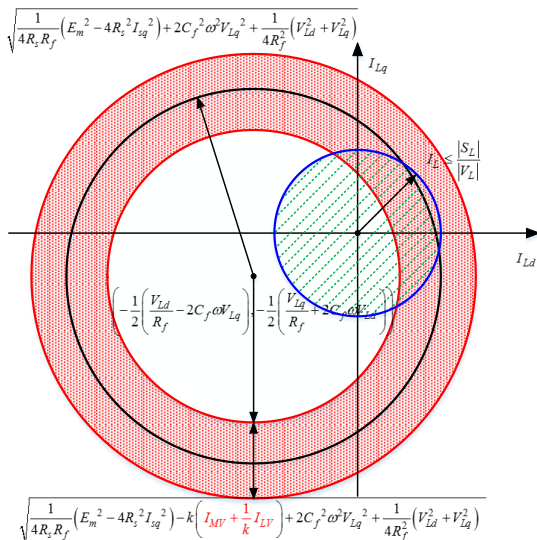


Fig. 3 variation of SST loading area as a function of injected power at embedded subsystems. The area inside two red circles shows the variations due to $I_{MV} + I_{LV}/k$.

PROPOSED CONTROLLER

To start the controller design, new state variables are defined to map the steady-state operating point to the origin of the Cartesian coordinate system of axis as:

$$\begin{aligned}
 x_1 &= i_{sd} - I_{sd}, x_2 = i_{sq} - I_{sq} \\
 x_3 &= v_{dc1} - V_{dc1}, x_4 = i_{fd} - I_{fd} \\
 x_5 &= i_{fq} - I_{fq}, x_6 = v_{Ld} - V_{Ld}, x_7 = v_{Lq} - V_{Lq}
 \end{aligned} \quad (16)$$

And, defining control laws as:

$$u_{1d} = U_{1d} + \Delta u_{1d} + k_d \int x_3(t) dt \quad (17)$$

$$u_{1q} = U_{1q} + \Delta u_{1q} + k_q \int x_2(t) dt \quad (18)$$

$$u_{2d} = U_{2d} + \Delta u_{2d} + k_r \int x_6(t) dt \quad (19)$$

$$u_{2q} = U_{2q} + \Delta u_{2q} + k_s \int x_7(t) dt \quad (20)$$

Each one of these laws have three parts where U_{1d} , U_{1q} , U_{2d} , and U_{2q} are available from the steady-state analysis. Integral parts are added for compensating steady-state errors due to uncertainties such as circuit parameters and measurements. But the third part is for constructing globally asymptotic stable control laws. This part is not defined yet and has to be formulated such that the time derivative of the positive definite Lyapunov function becomes negative definite. So, Δu_{1d} , Δu_{1q} , Δu_{2d} , and Δu_{2q} are obtained as

$$\Delta u_{1d} = \alpha (x_1 V_{dc1} - x_3 I_{sd}) \quad (21)$$

$$\Delta u_{1q} = \beta x_2 V_{dc1} \quad (22)$$

$$\Delta u_{2d} = \gamma \left(\frac{x_3}{k} I_{fd} - x_4 V_{dc2} \right) \quad (23)$$

$$\Delta u_{2q} = \delta \left(\frac{x_3}{k} I_{fq} - x_5 V_{dc2} \right) \quad (24)$$

Where α , β , γ , and δ are positive real numbers.

SIMULATION RESULTS

To evaluate the proposed controller, an SST with the parameters listed in the table I is used. Two types of disturbances are adopted for evaluating the performance of the proposed controller. The first is load variation that is shown by blue solid line in Fig. 4 and the second is DC port current variation that is a sine wave with frequency of 0.25 Hz shown by black solid line in Fig. 4. The sine wave is used to show the fast and vast variation of the connected subsystems. Fig. 5 shows the obtained results. It can be seen that the grid current has harmony with load variations and voltages track their references, effectively.

Table I parameters of SST for enabling MGs

Parameter	Value (unit)	Parameter	Value (unit)
R_s	1.1 (Ω)	V_{dc1}	500 (V)
L_s	10 (mH)	V_{dc2}	500 (V)
C	1000 (μ F)	α	6.78×10^{-8}
R_f	0.2 (Ω)	β	1.53×10^{-1}
L_f	5 (mH)	γ	3.76×10^{-5}
C_f	500 (μ F)	δ	4.82×10^{-5}
f	50 (Hz)	k_d	0.052
k	1	k_q	3.561
E_m	163.3 (V)	k_r	0.005
i_L	5 (A)	k_s	0.007

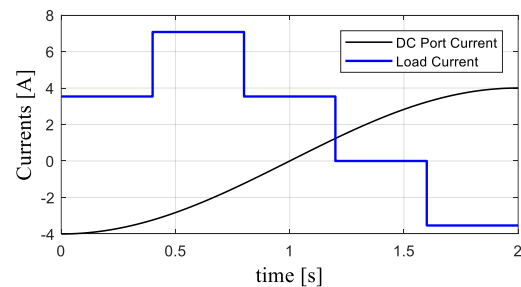


Fig. 4 Load current (blue solid line) and DC port current (black solid line) used in the simulations.

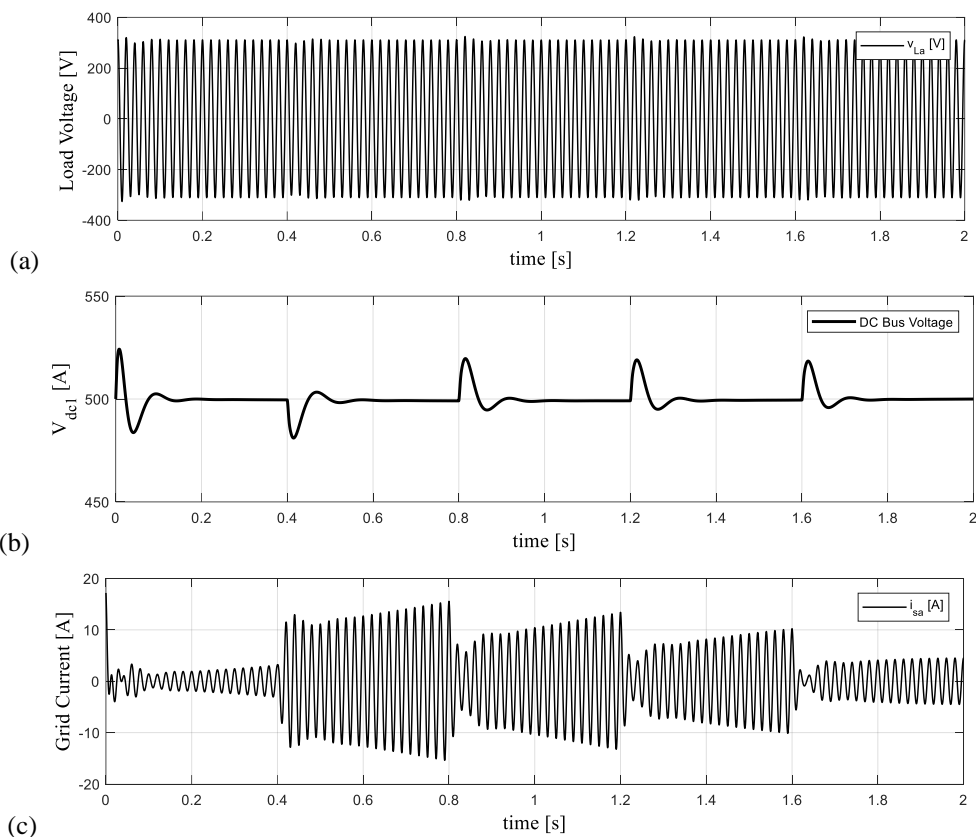


Fig. 5 simulation results based on simplified model of the SST; (a) Load voltage, (b) DC bus voltage, and (c) grid current.

CONCLUSION

In this paper, a Lyapunov based controller for ensuring asymptotic stability of the SST based MGs is presented. Integrators are added to final control laws to cancel the steady-state errors. Simulation results show that embedded subsystem at DC port of the SST with fast and vast variation in the injected power can not disturb the performance of the SST. Also, active power injections enhance the loading capability of the SST and passive powers limit its loading capabilities. Therefore, the SST based MGs that use such a controller preserve asymptotic stability of the system.

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