Modular DAB DC-DC Converter Low Voltage Side DC link Capacitor Two-Stage Charging-up Control for Solid State Transformer Application

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***Abstract*—This paper presents an effective two stage DAB charging-up control method for modular DC-DC converters with low voltage side common DC bus voltage starting from zero. In 1st stage of charging, the DAB controller is modified to allow variable duty cycle control of medium voltage side DAB converter. In this stage, a constant charging-up current is applied so that low voltage side DC link voltage is charged up linearly. In the 2nd stage of charging control, the normal dual voltage and current control loops are applied. At the end of 2nd charging up stage, the DAB controller is ready for normal power regulation. The proposed DAB charging control method is applicable for modular SST start-up application for both grid tied and standalone application. The important advantage of the proposed DAB charging control method is that the DC-DC converter performance is robust to DC-DC converter circuit parameter variation and operation condition variation among DAB modules. Another attractive advantage is that the proposed solution is purely DAB control algorithm change without requiring extra circuit component in start-up charging process.**

***Index Terms*—Solid state transformer (SST), dual active bridge (DAB), DC-DC converter, DC link, high frequency (HF) transformer, medium voltage (MV), low voltage (LV), zero voltage switching (ZVS).**

I. INTRODUCTION

The dual-active-bridge (DAB) DC-DC converter, consisting of two active bridges and a high-frequency transformer is becoming an appealing topology for bidirectional solid state transformer (SST) application. This paper presented the two stage DAB control method to smoothly charging up the LV side DAB DC link capacitor starting from zero voltage to its target value.

The contents of this paper are organized as below. In section II the start up charging process is described for the SST circuit configuration with modular DAB DC-DC converters. In section III the modular DAB control scheme for normal SST load/power regulation is presented. In section IV the modular DAB control scheme for LV DC link charging is presented. In section V the simulation results are presented for the proposed modular DAB LV DC link charging control method with larger DAB circuit parameter variation. To valid the stability and robustness of the proposed DAB control charging solution, the simulations are also performed for the dynamic transition from modular DAB charging control to normal modular DAB control in full load step-up change condition with larger DAB circuit parameter variation. The conclusions are presented in section VI.

II. SST START-UP CHARGING PROCESS

The SST start-up charging process for DAB DC-DC converters are explained for the SST circuit configuration shown in Fig. 1 which support either low voltage side grid tied power regulation or standalone power supply application. The cascaded modular H-bridge AC-DC converter of SST system is connected to the MV side AC grid through the grid filter inductor, a pre-charging resister and by-passing contactor circuit network, and a circuit breaker. The LV side output of modular DAB DC-DC converters is connected to a common DC bus. The LV DC bus of the SST system is connected to a single phase DC-AC inverter. The LV inverter can either operate in grid tired application by connecting to a LV AC grid voltage source through a circuit breaker or operate at standalone application by connecting directly to the load through a circuit breaker.

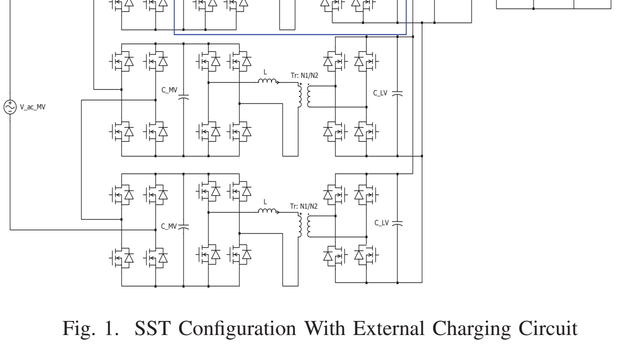


Fig. 1. SST Configuration With External Charging Circuit

For this circuit configuration, the MV side DC link capacitor can be pre-charged by freewheeling diode network of the cascaded H-bridge converter to certain voltage level. The MV side DC link voltage is further charged up and regulated at the target MV DC link voltage level by cascaded H-bridge AC-DC control system. It is desirable that the LV DC link capacitor can be charged up directly by the DAB DC-DC converter modules without extra charging circuit. At the end of DC-DC converter charging process, the LV DC link voltage should be regulated at the target voltage level. Afterwards, the LV side circuit breaker can be closed and LV side DC-AC converter is enabled for normal power regulation.

Many DAB control solutions have been proposed for normal power transfer operation of DAB converter with reduced switching loss and conduction loss. However, there is no published literature found in the application of DAB control for LV side DC link capacitor voltage charging. The conventional DAB control for normal power regulation cannot be used directly in DAB LV DC link charging control starting from zero voltage condition. Very large in-rush current will be generated in DAB converters which will well exceed the rated current limit of the DAB switching devices. This large in-rush current can also cause undesired fluctuation of MV side DC link voltage and create potential control stability issue for MV side converter control. The aim of this paper is to provide a control solution for this issue without extra hardware cost required.

III. MODULAR DAB CONTROL FOR NORMAL OPERATION

Fig. 2 shows 2-level full bridge DAB converter circuit which is the building block for the SST system shown in Fig. 1, where V1 is MV side DC bus voltage, V2 is LV side DC bus voltage. and I_{o2} is DAB converter LV side output current. There are two basic types of DAB control methods for normal power transfer operation. The first type is the single voltage loop DAB control method [1] and its enhanced variations with estimated load feed-forward to improve the dynamics response [2] [3]. The second type is the double voltage loop and current loop DAB control [4] [5] [6] [7] and its enhanced schemes by replacing the current measurement with estimation to improve inner loop BW by eliminating the low pass filter on feedback current signal [8]. For SST application, the dual voltage loop and current loop control scheme is preferred because of its control robustness with respect to circuit parameter variation and its flexibility to achieve optimized load/power sharing through proper current distribution. Fig.3 illustrated the double voltage loop and current loop DAB modular controller for SST system in normal power/load regulation control, where $\beta 1, \beta 2, \beta 3$ are the phase shift angle between MV and LV converter bridge of each individual DAB converter module, $d_{1\_1}, d_{1\_2}, d_{1\_3}$ are the duty cycle control signals of each individual MV side DAB converter module, and $d_{2\_1}, d_{2\_2}, d_{2\_3}$ are the duty cycle control signals of each individual LV side DAB converter module, and $I_{o2\_1}, I_{o2\_2}, I_{o2\_2}$ are LV side DC bus output current of the DAB modules.

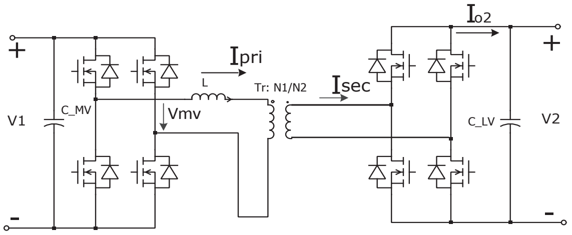


Fig. 2. 2-level full bridge DAB DC-DC Converter

In the dual loop DAB control system, the LV side voltage PI regulation is applied to generate the total current reference signal for entire SST DC-DC converter. The total load current is estimated and added as feed-forward current required for the entire SST DC-DC converter system. The total current reference is distributed between the DAB modules to generate the current reference for individual DAB current control loop. The current control loop is closed with the feedback current from low pass filtering of the measured LV side DC bus current of each individual DAB converter. The phase shift control signals $\beta 1, \beta 2, \beta 3$ for each DAB converter are generated by PI control regulation of the averaged LV DC bus output current of the corresponding DAB converter module. The MV side and LV side duty cycles of each DAB module are set individually according to the operation condition and the measured averaged current of each DAB to achieve optimized zero voltage switching (ZVS) operation of DAB converter. In practical implementation, an off-line characterized look-up table or simplified analytical function is applied to generate the MV and LV side DAB converter duty cycle signals to enlarge the ZVS range of DAB converter in wide operation range for the SST system. Normally the duty cycles are set to 100% at heavy load condition to increase the maximum power output capability of SST system [9]. At medium and light load conditions, the duty cycles of DAB module are reduced to create a current continuously flow condition to maintain the minimum magnetization current flow in the high frequency transformer primary windings to maintain the ZVS operation of DAB converter switches for the switching loss reduction [10].

The DAB controller described above is developed for the bi-directional power transfer regulation of DAB in the normal SST operation. In the SST start up process when DAB LV side DC bus is charging up from zero voltage, modification of DAB control is required to minimize the in-rush current at start of charging process.

IV. MODULAR DAB LV DC BUS CHARGING CONTROL

Fig. 4 shows modular DAB controller modification for LV DC link capacitor pre-charging in the SST start-up process based on the normal power flow control presented in Section III. As shown in Fig. 4, at the SST start-up process, the charging status detection function block is activated to check whether the pre-charging is still in-progress or the DAB LV DC bus charging has completed.

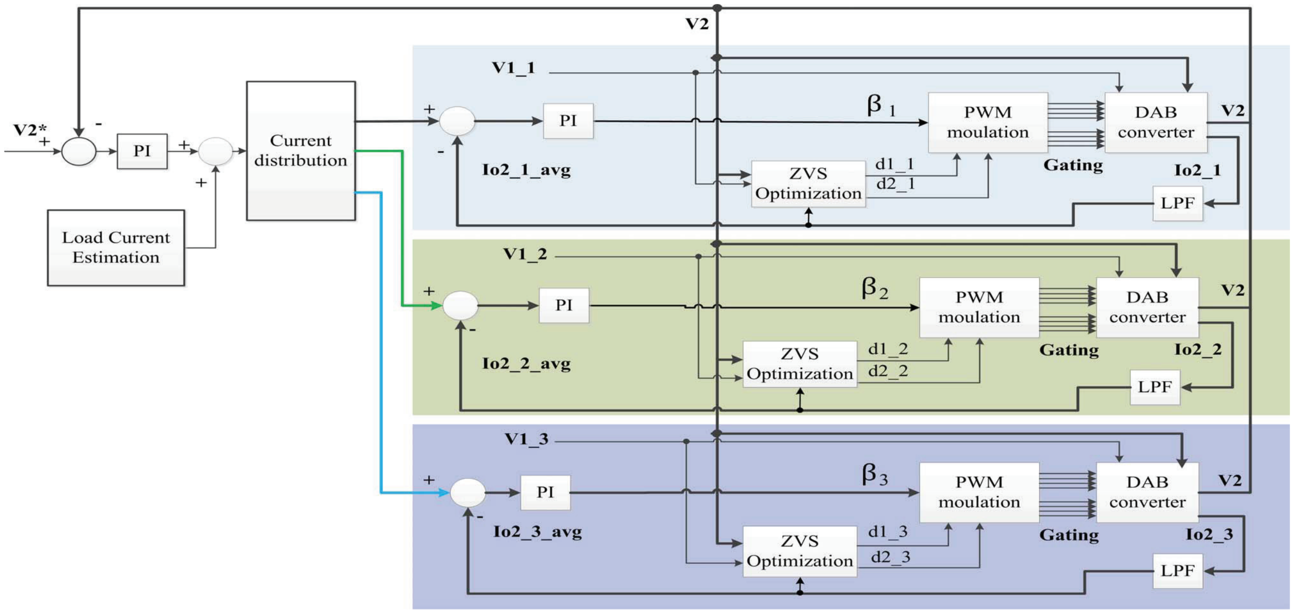
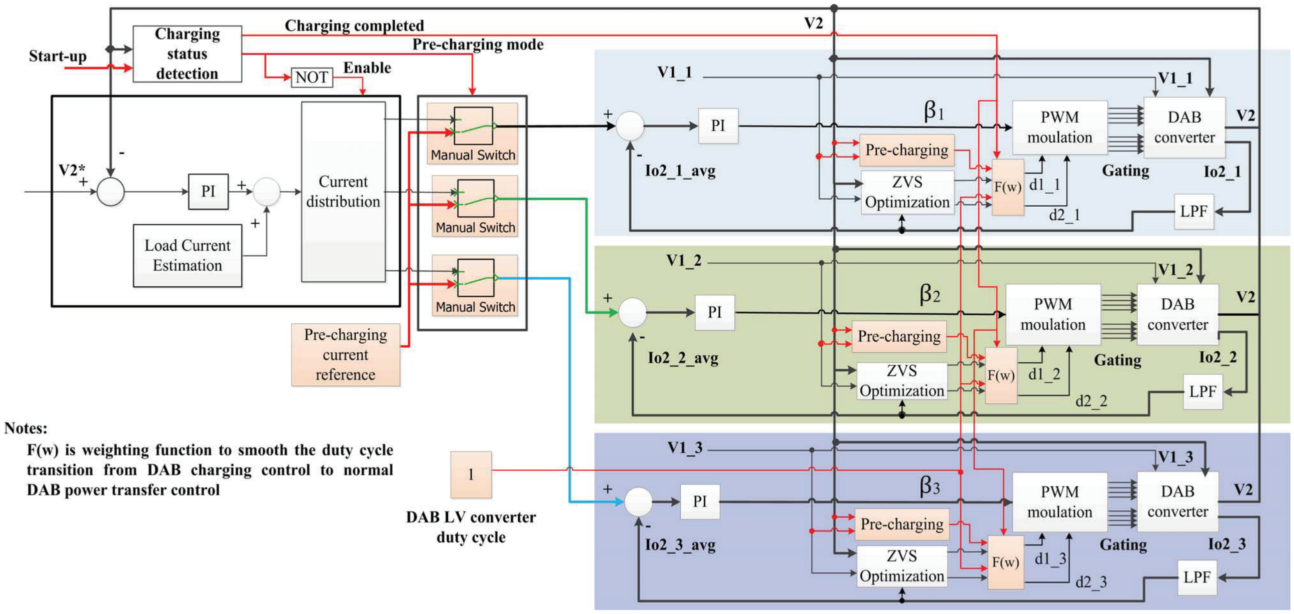


Fig. 3. Dual Voltage and Current Loop DAB Control

In the DAB pre-charging stage, the DAB control outer voltage loop is disabled. Only the inner current loop of each DAB module is activated. A smaller constant pre-charging current reference is set to all modular DAB current controller. The current controller output regulates the phase shift angle $\beta1, \beta2, \beta3$ of DAB converter for each individual DAB. The duty cycle of LV side DAB converter is set to 100%. The MV side DAB converter duty cycle is calculated from equations (1) (2) (3) respectively for DAB1, DAB2 and DAB3 with K_{adj} set to around 0.85 - 0.70.

At start of DAB controlled LV DC bus charging up, LV DC bus voltage $V2$ is closer to zero, the MV side duty cycle of the individual DAB converter modules $d_{1\_1} \approx d_{1\_2} \approx d_{1\_3} \approx 1 - k_{adj}$ are around $0.15 - 0.3$. With the increasing of LV DC link voltage, the MV side duty cycle of the individual DAB converter slowly increases. The maximum MV side DAB converter duty ratio is smaller than 1 in the entire DAB pre-charging stage. The DAB current loop dynamic is much faster than the MV side DAB duty cycle variation due to the small charging current and slow DC link capacitor voltage dynamics. Therefore, there is no stability concern about the LV DC link pre-charging current loop control with slow varying MV side



Notes:
F(w) is weighting function to smooth the duty cycle transition from DAB charging control to normal DAB power transfer control

Fig. 4. DAB Controller for LV Side DC link Precharging

duty cycle.

$$d_{1\_1} = 1 - k_{adj} * acos(Limit(V2/V_{1\_1}, 0, 1))/(pi/2) \quad (1)$$

$$d_{1\_2} = 1 - k_{adj} * acos(Limit(V2/V_{1\_2}, 0, 1))/(pi/2) \quad (2)$$

$$d_{1\_3} = 1 - k_{adj} * acos(Limit(V2/V_{1\_3)}0, 1))/(pi/2) \quad (3)$$

Fig. 5 shows the implementation diagram of the above MV side DAB converter duty cycle generation method for the DAB LV DC link bus pre-charging scheme. Once the LV DC bus voltage is above the threshold value, the second LV DC link charging stage starts with the normal power regulation control of DAB activated. The LV DC link voltage loop is applied to generate the charging current command. When the LV DC bus voltage is stabilized at its target value, the charging process is terminated and the DAB duty cycle control is smoothly transfered to normal optimized ZVS settings with the weight for the pre-charching duty cycle setting slowly reduced to 0 and the weight of normal setting slowly increased to 1. Afterwards, the normal DAB power transfer control is then fully activated and ready for LV side converter connection for normal power regulation.

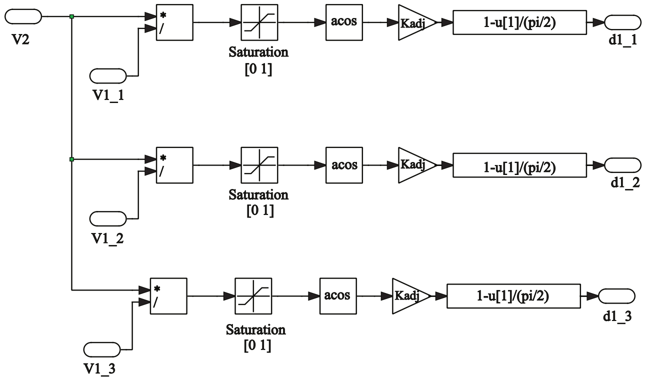


Fig. 5. DAB MV Side Duty Cycle Function for LV DC Bus Pre-charging

V. SIMULATION OF MODULAR DAB CHARGING CONTROL

To verify the performance of the proposed SST start-up modular DAB charging control scheme, PLECS circuit simulation is performed for the modular DAB circuit configuration shown in Fig. 6. Table. I shows the parameters used in the modular DAB control circuit simulation.

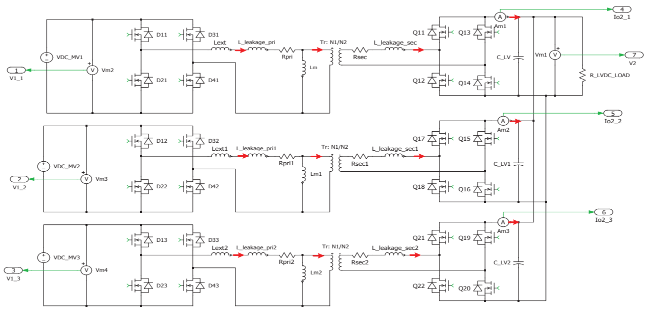


Fig. 6. Modular DAB for Charging Simulation

TABLE I
SIMULATION PARAMETERS OF MODULAR DAB DC-DC CONVERTER

Parameter	Symbol	Value
Number of DAB modules	N_{DAB}	3
Nominal power of each DAB module	P_{nom}	5000 W
DAB Switching frequency	f_{sw}	100 kHz
MV DC Bus Target Voltage	$VDC\_MV(V1\_1, V1\_2, ...)$	729 V
LV DC Bus Target Voltage	$VDC\_LV(V2)$	400 V
Transformer Magnetization Inductance	L_m	9.9797 mH
Transformer primary leakage Inductance	L_{pri}	0.5774 uH
Transformer secondary leakage Inductance	L_{sec}	0.0189 uH
Transformer primary AC Resistance	R_{pri}	0.0217 ohm
Transformer secondary AC Resistance	R_{sec}	0.0085 ohm
DAB External Inductance	L	92 uH
Transformer Turns Ratio	$N1/N2$	1.7778
LV side DC link Capacitance per DAB Module	$C_{LV}(C1, C2, C3)$	230uF

Fig. 7 shows the PLECS circuit simulation system with three DAB converter modules. The simulation starts with pre-charging enabled with zero initial voltage for all LV DC link capacitors. When the LV side DC link voltage reaches the threshold around 300V, the DAB controller switched to dual voltage/current loop control. The duty cycle control signals from pre-charging will be transfered to the normal duty cycle control with a smooth weighting function when the charging process is completed. The circuit breaker is closed after the charging process is completed to add a resistive step-up load change for full power operation of DAB converter modules. Fig. 8 shows simulation results of the control signals of DAB module (1) in LV side DC link charging process. In the pre-charging process, the averaged DAB LV side current follows the current reference. The phase shift angle starts from zero and slowly increases to a stable value. The MV side DAB converter duty cycle also starts from a very smaller value and slowly increases. When the voltage loop is closed in the charging process, the charging current of DAB module is quickly

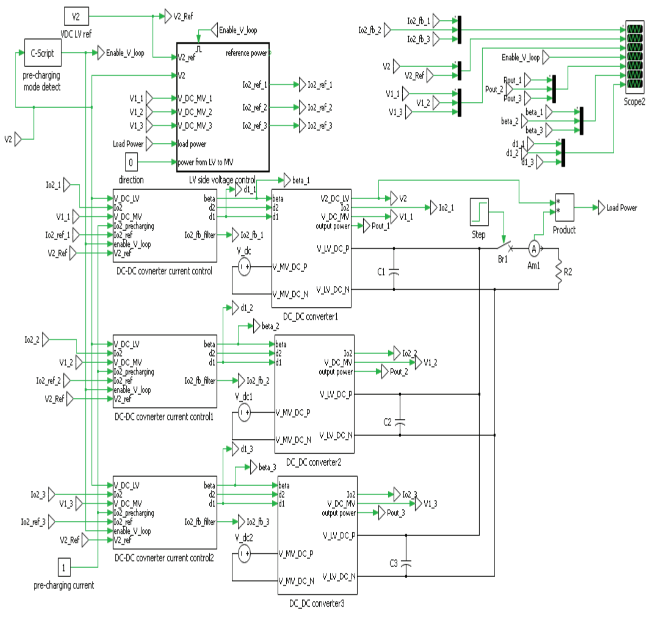


Fig. 7. Modular DAB Charging Control Simulation System

reduced when the LV voltage is approaching to its target value. The instantaneous LV side DC output current of the DAB module starts with a smaller value in the pre-charging process and slowly increases when the voltage regulation is enabled. No large in-rush current is generated in the entire charging process due to small duty cycle applied for MV side DAB converter control. Fig. 9 shows simulation results of the DAB converter output voltage and HF transformer voltage/current signals, and DAB output DC link current signals at the start of charging process. The simulation results show that MV side DAB converter duty ratio is very small, and the LV side DAB converter duty ratio is 100%. The transformer primary voltage and secondary voltage slowly increases starting from nearly zero voltage. The transformer primary winding and secondary winding current both are small at the start of charging. The LV side DC link output current of the DAB module is also very small at start of charging process. Fig. 10 shows simulation results of the modular DAB converter with +/-20% external inductance value variation with pre-charging current reference set to 1A. This simulation result shows that phase shift angles of each DAB module are different. However the charging power difference for each DAB module is very small. This simulation results validate that applying the proposed DAB charging control solution, the modular DAB control performance is not sensitive to the larger variation on the external inductance in DC-DC circuit. This is one of the major benefit of applying closed-loop current control of each DAB module in charging control process. Fig. 11 shows simulation results of modular DAB current and power performance for the proposed two-stage DAB LV DC link charging process. In this simulation, the MV side DC link voltage unbalance of +/-50V is applied for the three DAB modules. The pre-charging current reference is set to 1.0A. The simulation results show that in the DAB pre-charging stage, the MV side duty cycle and phase shift angle are different for each DAB modules. However all the three DAB modules follow the same current reference, and the charging power difference is very small for individual DAB module. This means that the proposed pre-charging control performance is not sensitive to the MV side voltage unbalance among converter modules. Fig. 12 shows the transit simulation results of modular DAB converter control from charging control to normal power control in full load step-up change condition with +/-20% external inductance variation in DAB circuit. This simulation result shows that the MV side duty cycle is smoothly transfered from the pre-charging setting to 100% duty cycle in full load operation, which is a desired control behavior to achieve maximum power output of all DAB modules. The modular DAB control is

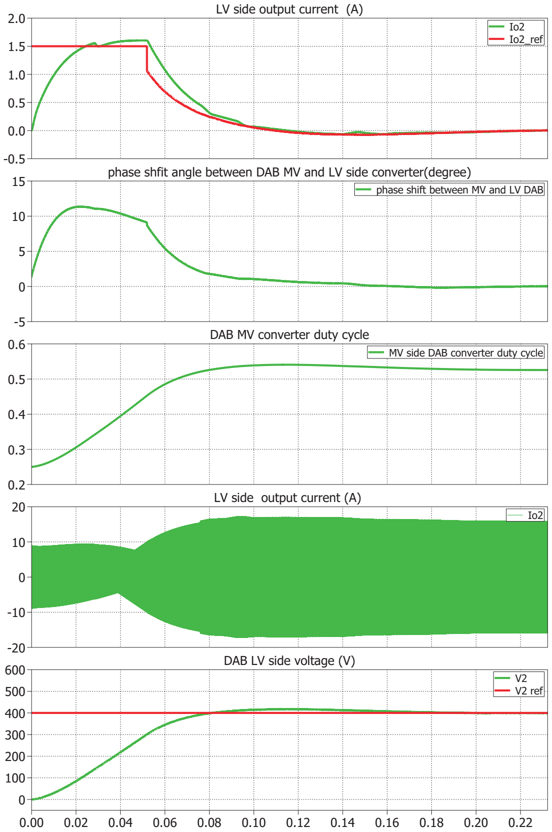


Fig. 8. DAB Control Signals In LV DC Bus Charging Process

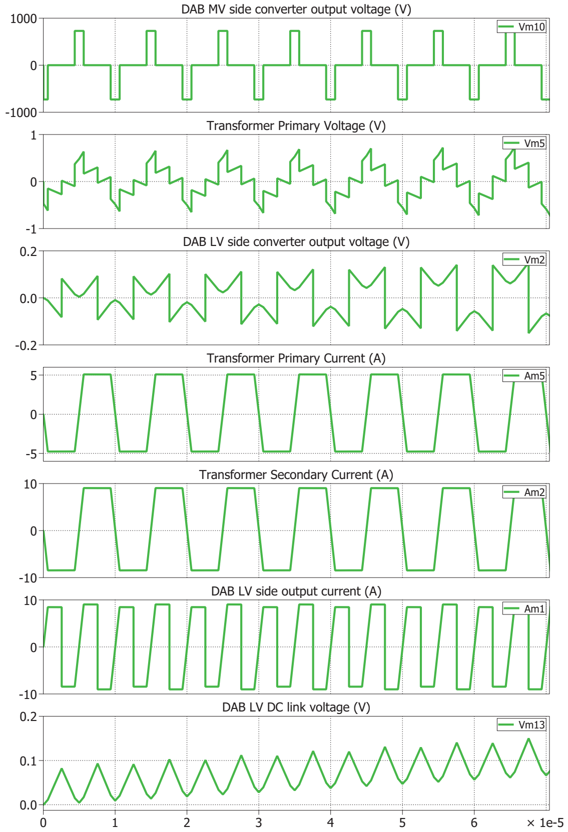


Fig. 9. DAB Control Signals In LV DC Bus Charging Process

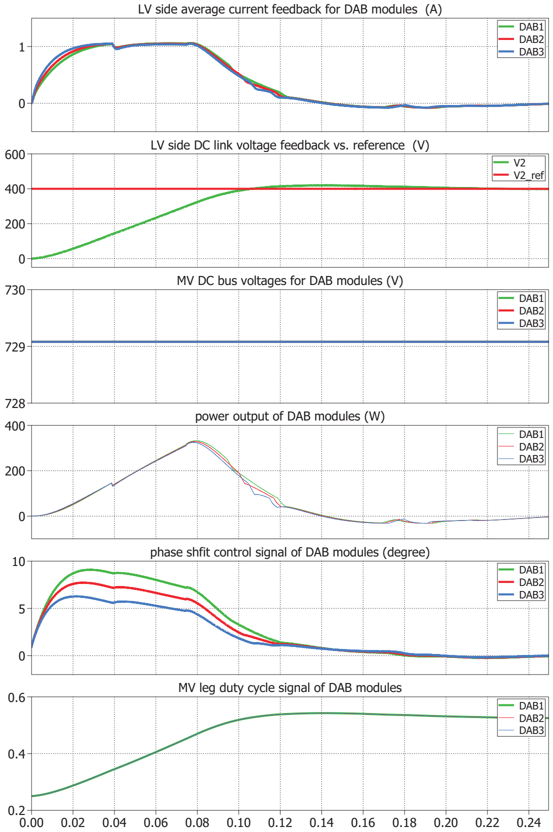


Fig. 10. Modular DAB Charging Control with +/-20% External Inductance Variation

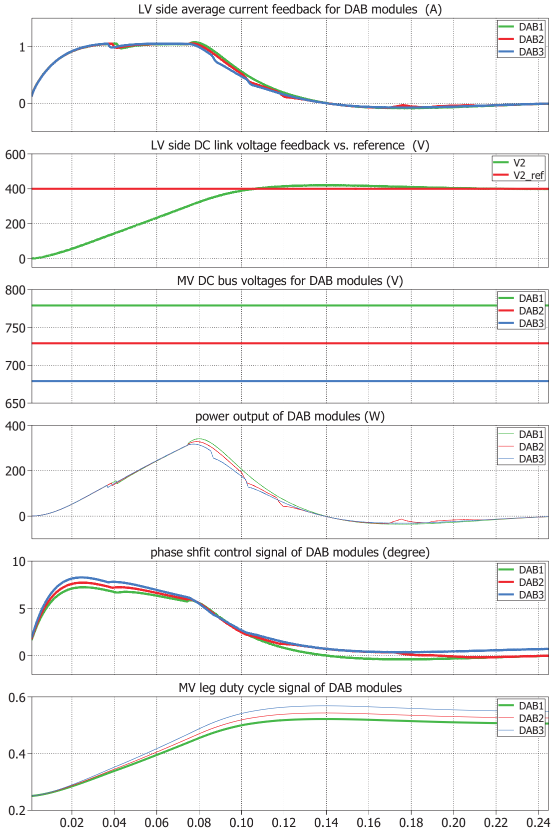


Fig. 11. Modular DAB Charging Control with +/-50V MV DC Voltage Unbalance

stable in the full load step-up dynamic transition even with a larger DC-DC converter inductance unbalance. The DAB circuit inductance variation causes phase shift angle difference among DAB modules, but the output power difference among DAB modules is pretty small. This simulation results validate that the modular DAB performance is not sensitive to the DAB inductance variation in full load operation. Fig. 13 shows transit simulation results of modular DAB control in full load step-up change condition with MV DC link voltage unbalance of +/-50V. The pre-charging current reference is set to 1.0A in this simulation. The simulation result shows that the MV side duty cycle transition is smooth in full load step-up change process. The modular DAB control is stable even with larger MV DC link voltage unbalance. In the full load operation, the voltage loop will distribute more current to the DAB module with higher MV DC link voltage to help to restore the MV DC link voltage balance. This is the reason that the simulated current and power are different among DAB modules.

VI. CONCLUSION

This paper presents a practical method to charge up the LV side DC link of modular DAB DC-DC converter from zero voltage in the SST start-up process using modified modular DAB control method without requiring extra external hardware charging circuit.

The DAB controller modification from charging control to normal operation is simple. In the first stage of charging control when the LV DC link voltage starts from zero, the MV side DAB converter duty cycle is computed as the function of the ratio of LV side DC link voltage and MV DC link voltage to ensure a very small MV duty cycle to be applied at start of charging control. In this stage, DAB LV side voltage control is disabled. A very small constant charging current reference is given to the current loop of each DAB module. These two modifications in the precharging control ensure that the instantaneous charging current is under control from starting of DAB charging process. The second charging stage starts when LV side DC link voltage is closer to its target value. In this stage, the normal DAB control is activated by closing the outer voltage control loop to further charging up and regulate the LV DC link voltage around its target value. A smooth duty cycle transition to normal optimized ZVS setting is ensured by implementing a slowly varying weighting function. The close similarity of DAB charging controller structure and the DAB controller structure applied in normal power transfer control makes it easier to achieve smooth DAB control transition for

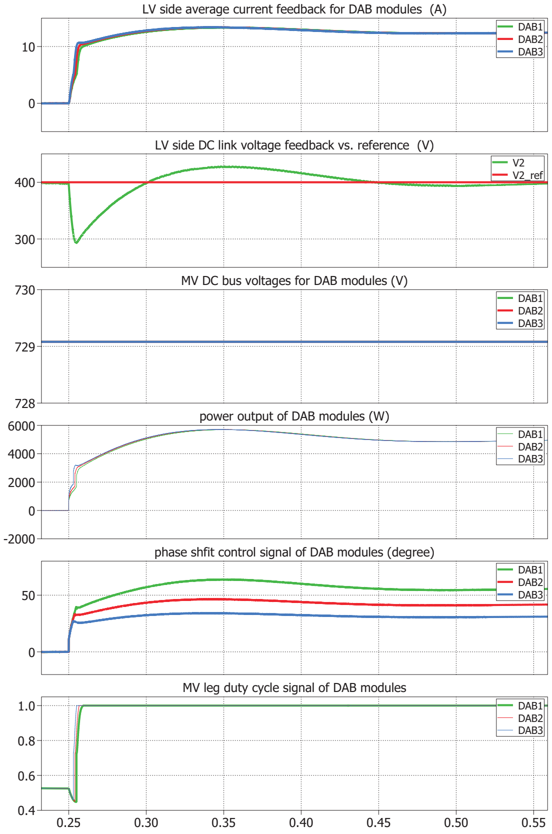


Fig. 12. Modular DAB Control Transition From Charging to Full Load Step-up with +/-20% External Inductance Variation

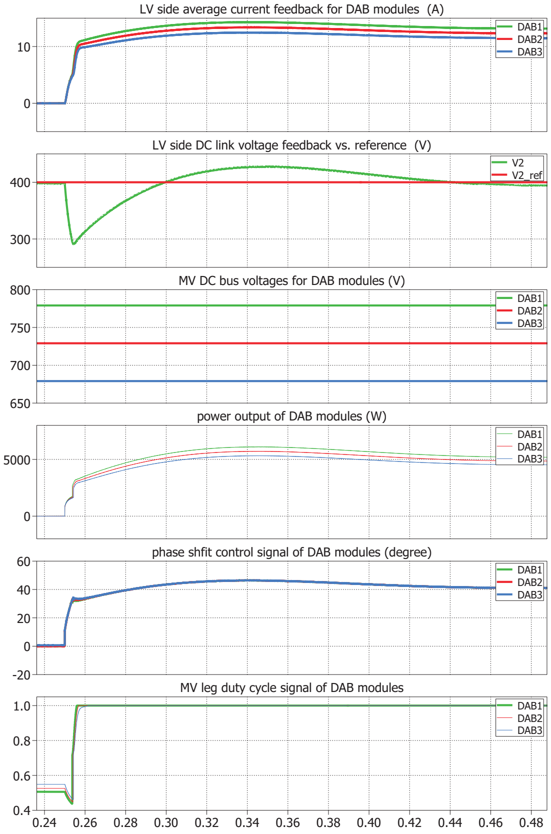


Fig. 13. Modular DAB Control Transition From Charging to Full Load Step-up with +/-50V MV DC Voltage Unbalance

power regulation.

The performance of the proposed solution has been verified using PLECS circuit simulation. The simulation results validate that the proposed modular DAB charging control is robust with respect to large DAB inductance variation and large MV DC link voltage unbalance. The transition from modular DAB charging control to normal modular DAB control is smooth and stable for full load step-up change with very large unbalanced DAB circuit inductance variation and very large MV DC link voltage unbalanced. The proposed solution is applicable for SST LV side operation for both standalone power supply application and the grid tied power regulation application.

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