Buck and Boost Start-up Operation of a Three-Port Power Supply for Hybrid Vehicle Applications

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Abstract— In future hybrid automotive applications there will be multiple voltage systems in a single vehicle. It is desirable to have bi-directional, isolated power flow between these different voltage levels. The three-port power converter is able to achieve full bi-directional power flow by using a high-frequency transformer, with three windings, connected to a full-bridge converter on each winding or port. The normal control of the power flow between the ports is via phase-shift control of the individual full-bridge converters. However in the automotive application, there may be only a single power source for the initial powering up of the system and in this case, phase-shift control can not be used to start-up the converter system. This paper presents a start-up method for the three-port converter in which the converter is first operated in a buck-mode, followed by an output voltage boosting mode, and is able to finally operate with normal phase-shift control. Detailed analysis of the buck and boost mode during start-up is presented and verified by simulation.

I. Introduction

In future hybrid automotive applications there will be multiple voltage systems in a single vehicle consisting of a conventional 14V network, the new 42V network, and a high voltage (200-300V+) network for traction systems [1]. It is desirable to have the ability for bi-directional isolated power flow between all of the different voltage networks since the power rating for the vehicle's 14V electrical accessories will be up to 2kW [2]. One such power supply that is able to achieve this full bi-directional power flow is the three-port converter (**Fig.1**, [3]), which uses a high-frequency transformer with three windings. The control of the power flow between the ports is via the phase-shift control of the individual full-bridge converters operating in square-wave mode. The three-port system was previously proposed by the authors for an UPS application [3]. In that paper the power flow between the ports was analyzed for phase-shift control, and characteristic waveforms for steady state operation and the system losses were determined.

For a hybrid automotive application, it is likely that the car's electrical system has a single energy source available for the start-up, such as a 12V battery (port 3 shown in Fig.1). During this initial start-up there may not be any voltage present on the 42V (port 2 shown in Fig.1) and/or the high voltage bus (port 1). If these two ports have near zero voltage on their output capacitors then the converter system can not transfer any active power to these two ports under the phase-shift control mode [4]. Therefore phase-shift control between converters can not be used during the start-up phase. The literature has not adequately presented any solution to this problem therefore this paper presents a suitable start-up method for multi-port converters.

To start-up the system the three-port converter is initially operated in a buck mode so that the starting port provides the charging current for the capacitors, e.g. C_1 and C_2, on the other two ports. Once the other two ports have sufficient DC voltage then normal phase-shift, bi-directional control of the system can occur. At start-up the battery source may only provide 12V on the low voltage port that is normally designed and

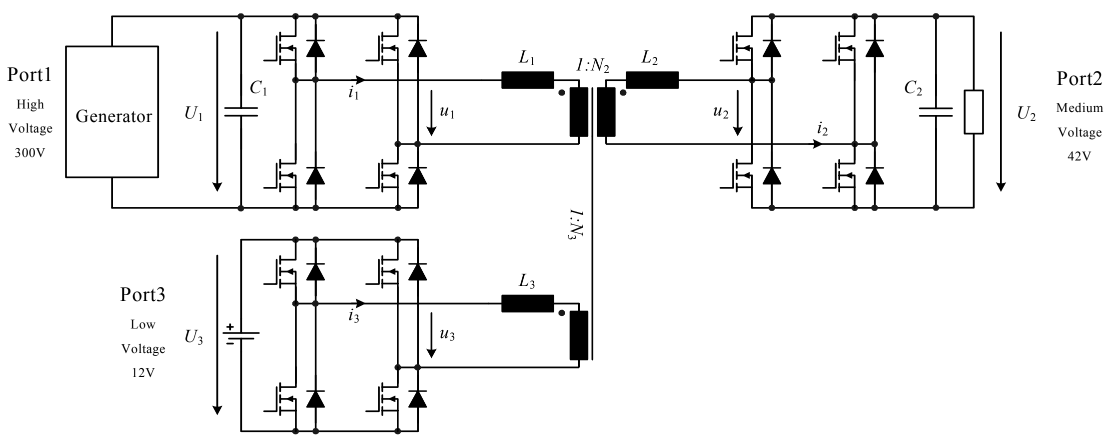

Fig. 1: Three-port high-frequency link converter for hybrid vehicle applications.

optimized for a nominal operating 14V system. Therefore, to reach the full operating voltages at the other two ports the power supply has to be operated in a voltage boosting mode. This can be achieved by individually controlling the switches on the other ports, i.e. by changing from buck mode operation to a boost mode.

This paper presents and analyzes the buck, boost and phase-shift operation of the three-port power supply during the start-up phase. To simplify the initial analysis the buck and boost operation of a two-port bidirectional full-bridge DC-DC, one converter connecting the 12V battery (port 3) to the 300V load side (port 1), is first discussed in **Section II**. Based on this, the operation of the three-port power supply including peak current limiting is discussed in **Section III**. The theoretical analysis of the three-port system start-up is then verified by simulations in **Section IV**.

II. Buck and Boost Operation of a Two-Port Converter

A two-port bidirectional converter, shown in **Fig.2**, is formed by two full-bridge converters made up of switches S_1–S_4 and S_5–S_8, where the isolation transformer interconnecting the battery (12V) and the load side (300V) integrates a stray inductance L_1. To simplify the analysis all the switches and anti-parallel diodes are assumed ideal, and the switch dead times are neglected.

A. Operation in buck mode

The switching waveforms for buck mode operation in discontinuous current mode (DCM) and continuous current mode (CCM) are shown in **Fig. 3**. In both cases the duty cycle of the switches S_1–S_4 is set at 50%. Operation of switches S_1/S_3 and S_2/S_4 is complementary to ensure no shoot-through current occurs on any phase leg. The gate signals of S_1 and S_2 have a leading phase ϕ which can vary from 0 to 50% of the period compared to those of S_3 and S_4. All switches S_5–S_8 remain in the off-state; therefore the load port full-bridge converter purely rectifies the transformer secondary voltage.

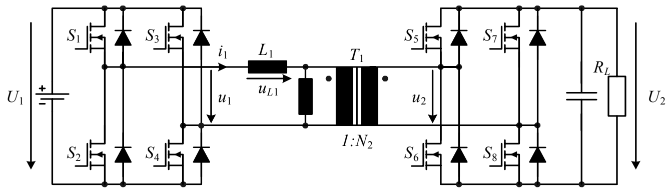

Fig. 2: A two-port bidirectional DC-DC converter.

As shown in Fig. 3(a) the current of L_1 is discontinuous and there are two main intervals occurring in one switching period, interval 2S2D (2 switches and 2 diodes conducting) and interval 1S3D (1 switch and 3 diodes conducting). In the interval 2S2D, the diagonal switches S_1 and S_4 (or S_2 and S_3) are on, and the current in the stray inductance starts increasing from zero. The energy from the input battery is partly transferred to the load and is partly stored in the inductance L_1. During the interval 1S3D, the two upper switches S_1 and S_3 or the two lower switches S_2 and S_4 are turned on and the energy stored in the stray inductance L_1 is transferred to the load. When the current decreases to zero no further energy is transferred to the load. This switching cycle constitutes a buck-type, DCM operation of the circuit. Using a flux balance consideration for inductance L_1, the resulting steady-state load voltage U_2 is calculated as

$$U_2 = \frac{\phi U_1}{2N_2 L_1 f_s}\left(\sqrt{\phi^2 {R_L}^2 + 4L_1 f_s N_2^2 R_L} - \phi R_L\right) \tag{1}$$

where f_s is the switching frequency of the converter, N_2 is the turns ratio of transformer, and R_L is the load resistance.

The operating mode of the converter in CCM is illustrated in Fig. 3(b). The phase angle, ϕ, is larger than for the DCM case and the voltage at the load side of the transformer is higher. When the converter is operating in CCM, an additional interval 4D appears, besides interval 2S2D and interval 1S3D, when the anti-parallel diodes of the switches are conducting. This is because the current of the stray inductance is negative (or positive) although gate signals are applied to the diagonal switches S_1 and S_4 (or S_2 and S_3). The load voltage U_2 can be

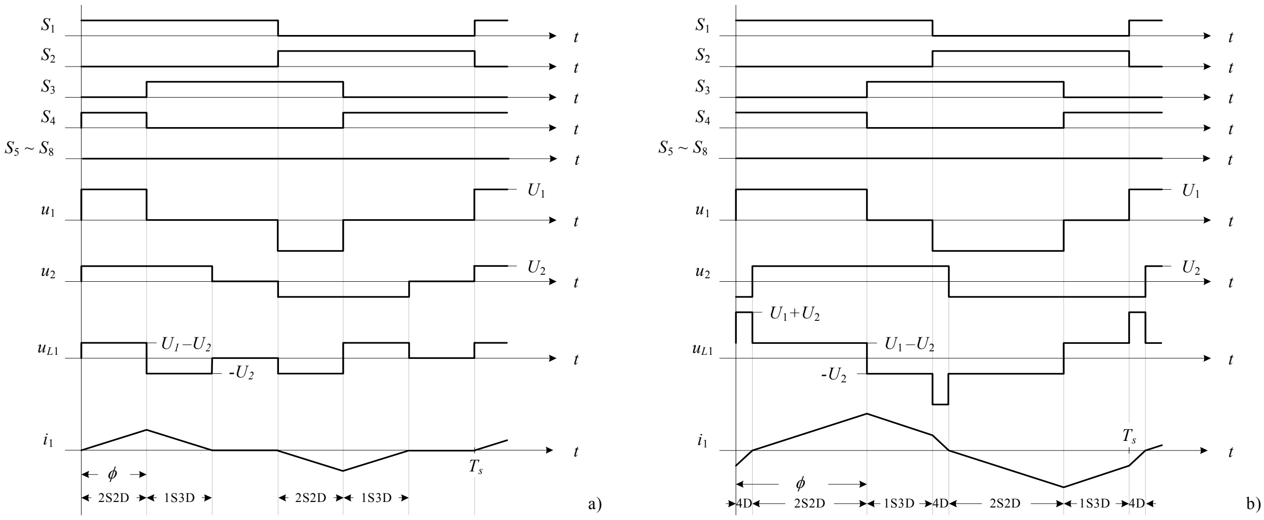

Fig 3. The switch signals for start-up in buck mode and key waveforms for DCM buck (**a**) and CCM buck (**b**) operation.

derived as

$$U_2 = \frac{U_1 N_2}{R_L}\left(\sqrt{\phi R_L{}^2 - \phi^2 R_L{}^2 + 4N_2^4 L_1^2 f_s^2} - 4N_2^2 L_1 f_s\right) \qquad (2)$$

The phase angle at which the converter operation moves from DCM to CCM can be calculated from

$$\phi = \frac{R_L - 4N_2^2 L_1 f_s}{2R_L}\,. \qquad (3)$$

The resulting load voltage U_2 as a function of phase shift ϕ is depicted in **Fig.4**(a). For the operating parameters given in Fig.4(a) the boundary between DCM and CCM occurs at a duty cycle of 0.41.

From the key waveforms shown in Fig.3 it can be seen that the switches S_1–S_4 are turned on and off under zero-voltage switching (ZVS) or partially in zero voltage, zero current switching (ZVZCS) conditions when the converter operates in DCM. Since the anti-parallel diodes of the switches S_5–S_8 are commuting naturally at zero current there is no significant reverse recovery.

B. *Operation in boost mode*

Once the phase angle has increased to 50% of the period the output voltage is determined mainly by the input voltage and the transformer turns ratio. The output voltage can only be further increased by operating the converter in a boost mode, where the switches on the load-side are operated. The switching signals and key waveforms for the boost mode are shown in **Fig.5**. The duty cycle of the switches S_1–S_4 is set to

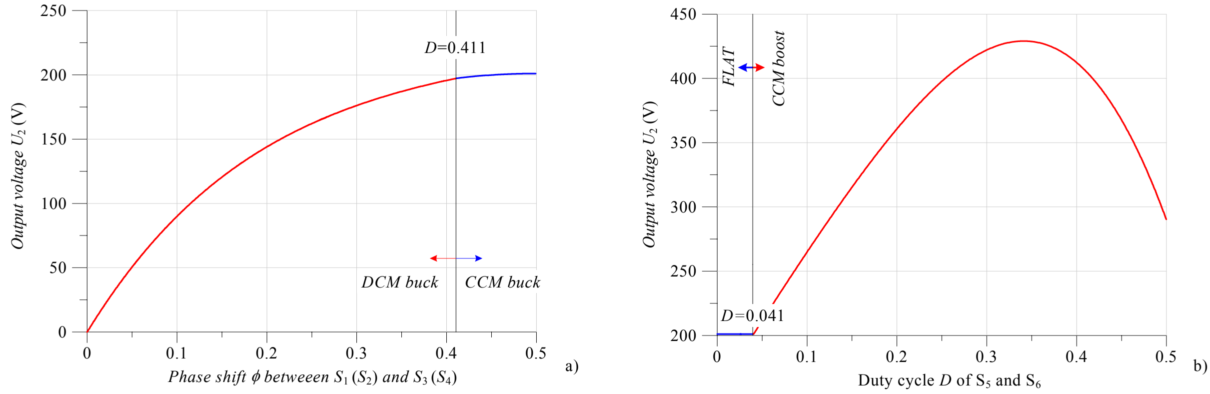

Fig.4: (**a**) Output voltage U_2 versus phase shift ϕ for buck-type operation. (**b**) Output voltage U_2 versus duty cycle D for boost mode. Assumed operating parameters: U_1=12V, f_s=100kHz, L_1=0.2µH, N_2=20, R_L=180Ω (assumed load on 300V bus is 0.5kW).

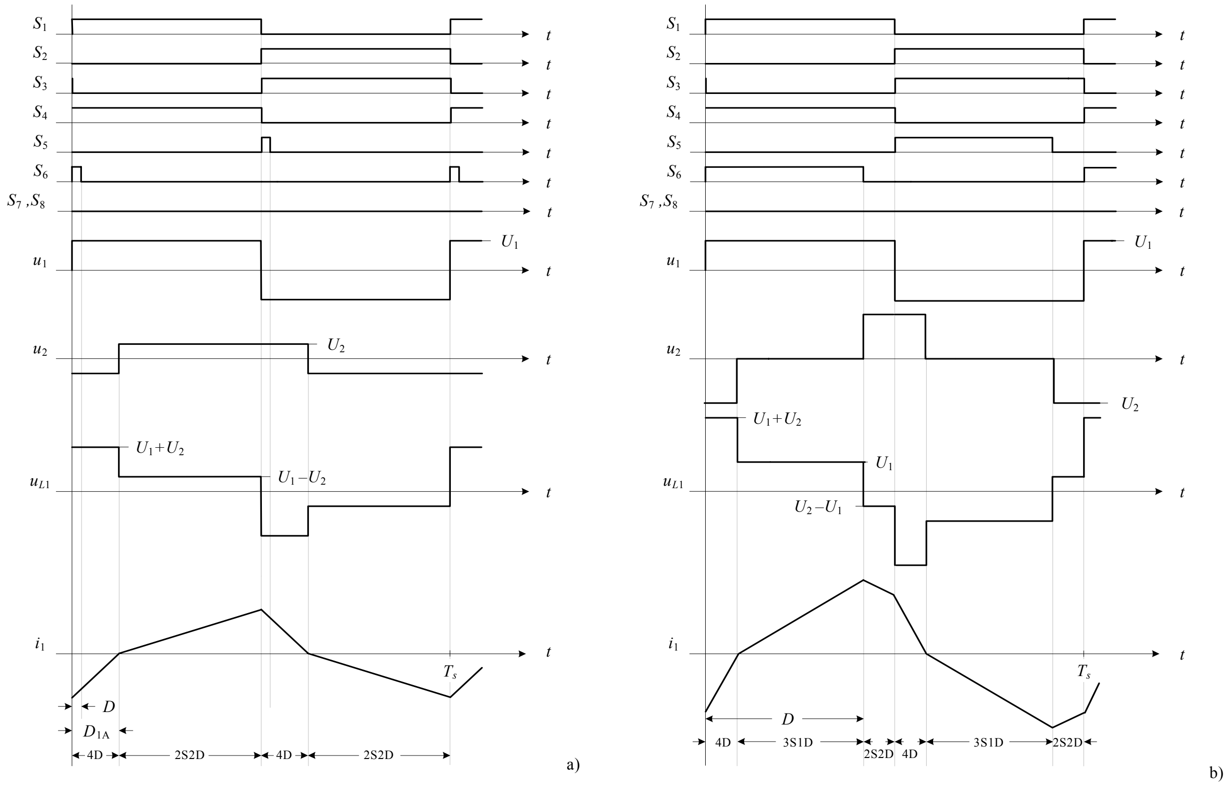

Fig.5: The switch signals for start-up in boost mode and key waveforms for FLAT mode (**a**) (cf. Fig.4(b)) and CCM boost (**b**).

50% and the switches S_1 and S_2 are controlled complementarily. The gate drive signals of S_1 and S_4 (S_2 and S_3) are always identical. The duty cycle, D, of the gate drive signal for S_5, which has a 180° leading phase compared to that of S_6, can vary from 0 to 50%. Switches S_7 and S_8 remain off.

A switching period is formed by three main intervals, interval 3S1D, interval 2S2D and interval 4D, as shown in Fig. 5(b). In interval 3S1D, switches S_1, S_4 and S_6 (or S_2, S_3 and S_5) are turned on, and the current in the stray inductance increases from zero and the input energy is totally stored in the stray inductance L_1. In interval 2S2D, S_6 (or S_5) is turned off, and the energy stored in the stray inductance L_1 together with energy from the input is transferred to the load. From Fig. 5 it can be seen that the switches are turned on and off under the ZVS condition. A third interval 4D appears when the anti-parallel diodes of the switches S_2, S_3, S_5 and S_8 (or S_1, S_4, S_6 and S_7) are conducting when the current of the stray inductance is positive (or negative).

If the duty cycle D is smaller than

$$D_{1A} = \frac{R_L + 4N_2^2 f_s L_1 - \sqrt{16N_2^4 f_s^2 L_1^2 + R_L^2}}{4R_L} \tag{4}$$

the converter operation changes from CCM to a “FLAT” (constant output voltage) mode. In this “FLAT” mode the load voltage is constant as the pulse period is formed by only two intervals, interval 4D and interval 2S2D. Fig.4(b) shows the load voltage of U_2 as a function of duty cycle of switches S_5 and S_6. It can be seen that the duty cycle has to be greater than 0.041 before any boosting of the output voltage occurs.

III. START-UP SCHEME AND CONTROL

A. Start-up Scheme

A block diagram of the control implementation for the start-up is shown in **Fig. 6**. There is one overall PWM modulator that is generating the gate control signals for all of the ports. During the start-up phase the PWM modulator produces gate signals with a 50% duty cycle for the low voltage (12V) port. The switches of the other two ports are off when the converter is operated in buck mode. Since the 12V system is providing the power to charge the 300V and 42V ports there needs to be over-current protection provided for the converter in case of excessive load or a short-circuit on the two other ports. This is achieved by measuring the 12V port transformer current and then turning off the active switches to limit the current.

In a hybrid car application it is assumed that the loads connected to the higher voltage ports will be disconnected during the start-up. Once the correct operating voltages are established the car’s central controller would then activate and control the loads attached to each port. Therefore it is assumed that some small amount of load (50W) is continuously connected to each of the higher voltage ports during the start-up.

For the start-up the battery source may only provide 12V on the low voltage port that is normally designed and optimized

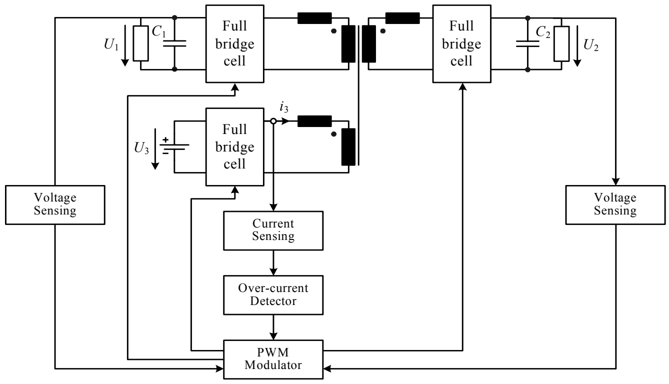

Fig.6: Block diagram of PWM control implementation for start-up.

for operation at a nominal 14V. Therefore to reach the full operating voltages at the other two ports the power supply must be operated in a voltage boosting mode.

The sequence for start-up operation is that the converter is initially operated in the buck mode until 50% effective duty cycle is achieved. To achieve an output voltage closer to the required value, the control strategy then changes to the boosting mode. Once the required output voltage is achieved the start-up controller then changes to the phase-shifting mode to regulate the load voltage to their nominal level. If the load current levels are sufficiently low then it is possible to skip the boost mode, moving directly from the buck mode to the phase-shift mode, without excessive currents occurring.

B. Current Limiting

In order to protect the converter from excessive currents, instantaneous current limiting is implemented by turning off a combination of switches depending on the operating mode. For example, when operating in the buck mode with positive current in L_3 and an excessive current is detected, the controller turns off switch S_{12} (complementary switch S_{11} is turned on, Fig. 8) to decrease the current. In the boost operating mode it is also necessary to turn-off the switches on the boosting port.

C. Three-port power supply control strategy

During the buck mode only one variable can be controlled and that is the phase shift angle between the phase legs of source converter. This single variable does not allow an individual control of the two output voltages. Therefore, phase-shift mode is always required when the voltages of the other two ports should be controlled individually.

To have independent control of the two load voltages a decoupling controller (cf. **Fig.7**) is required since the model of the power supply under phase-shift control is a two-input two-output system. The design of the decoupler is presented in [3]. The limiting value for ϕ_1 and ϕ_2 is $\pm\pi/2$ since the transferred powers reach a maximum. In the controller the limiting value is set to ±1.5 in order to guarantee the system matrix of the power supply is non-singular, thus ensuring a decoupling matrix exists as this is formed from the inverse matrix of the system matrix.

Another issue in the decoupling control of the three-port

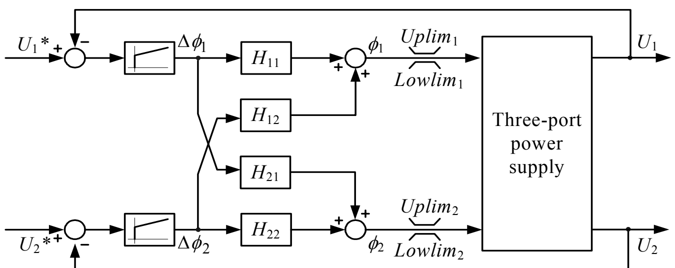

Fig.7: Output voltages control employing a decoupling network. U_1^* and U_2^* are the reference signals of the load voltages U_1 and U_2. The phase shift of control signals of u_1 and u_3 is denoted as ϕ_1; accordingly, ϕ_2 denotes the phase displacement of u_2 and u_3. ϕ_1 and/or ϕ_2 are defined as positive when u_3 is leading u_1 and/or u_3 is leading u_2.

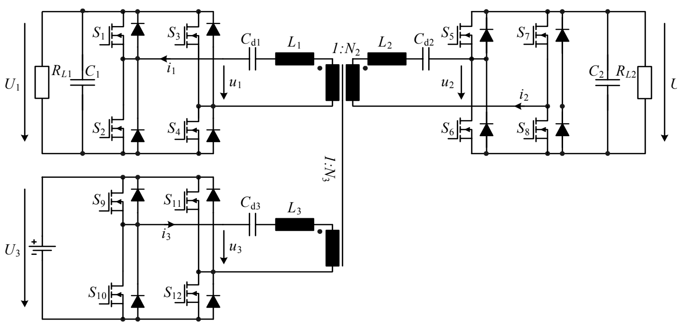

Fig.8: Circuit schematic employed for the circuit simulation. U_3=12V, L_1=40μH, L_2=4.4μH, L_3=0.1μH, C_{d1}=1.25μF, C_{d2}=10μF, C_{d3}=500μF, N_2=3/20, N_3=1/20, C_1=220μF, C_2=330μF, R_{L1}=1.8kΩ (assumed start-up load on 300V bus is 50W), R_{L2}=35Ω (assumed start-up load on 42V bus is 50W), f_s=100kHz.

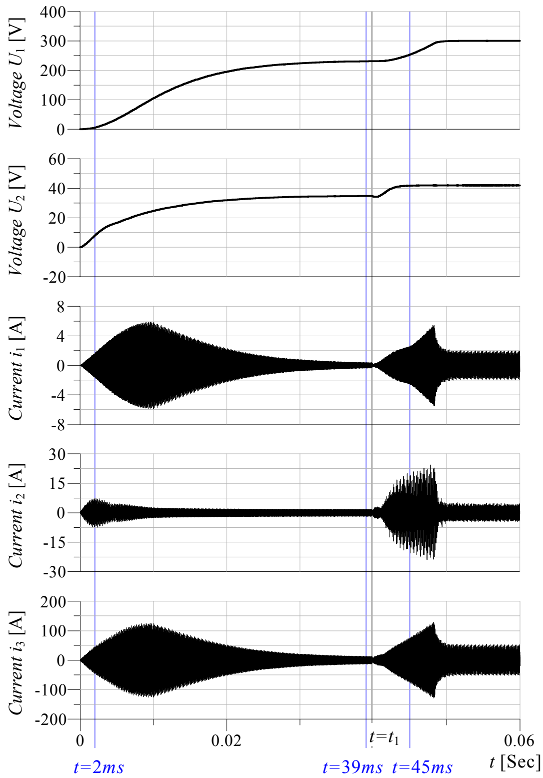

Fig.9: Simulation of the start-up scheme for three-port power supply.

converter is that the ratio of ϕ_1 to ϕ_2 should be kept even if the values of ϕ_1 and ϕ_2 are limited in order to be sure that the two loops are decoupled. If the absolute value of ϕ_1 is bigger than that of ϕ_2, the limiting value of ϕ_1 is ±1.5 then the limiting value of ϕ_2 should be set to $\pm 1.5*\phi_2/\phi_1$.

IV. Simulation Results

In the new-generation Toyota Prius the high voltage system to 14V DC/DC converter is rated at 1.4kW and the air-conditioning inverter at 2.6kW [6]. Therefore, the three-port power supply is assumed to have, under normal phase-shift operation [3], a maximum of 2kW being transferred from port 1 (high voltage generator) to port 2 (42V sub-system) and 1.5kW being transferred from port 1 to port 3 (14V sub-system). At this normal operation point, the peak current of i_1 is 20A, the peak current of i_2 is 73A and the peak current of i_3 is 170A. The three-port converter schematic and component values are given in **Fig.8**.

The start-up operation of the three-port converter is verified by digital simulations using PSIM. **Fig. 9** shows the simulation waveforms of the start-up process with the proposed start-up scheme, while Figs.10 to 12 show the detailed switching waveforms at the various time instants shown on Fig.9. During the start-up it is assumed a 50W background load is connected on each load port. From the simulation results, the peak

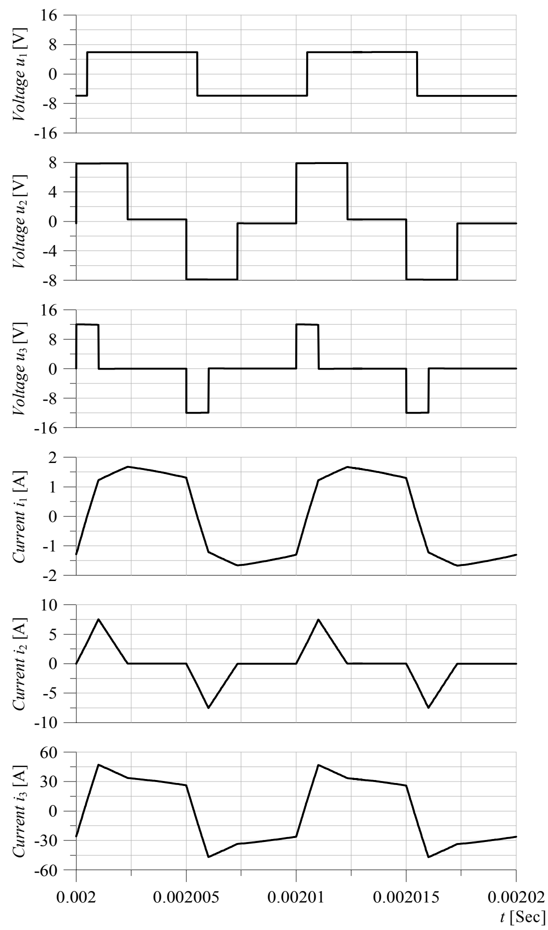

Fig.10: Simulation waveforms of the start-up scheme at t=2ms.

currents in each of the three ports are all lower than what is expected from normal operation. Therefore, the converter does not operate in current limiting mode during the start-up.

In this simulation there are two distinct intervals, one from time t=0 to time $t < t_1$, and the other for time $t \geq t_1$. In the first interval, the power supply is operating in buck mode. At the beginning of this interval (cf. **Fig. 10**), the phase-shift angle of the source converter (port 3) increases linearly to realize a soft-start, and to ensure the current is less than the maximum allowable. It can be seen that the waveform of the current i_2 is same as the DCM buck current in Fig.3(a) and the waveform of the current i_1 is same as the CCM buck current in Fig3(b). This occurs because the 300V capacitor requires more charge than the 42V capacitor. Therefore the charging current of port 1 is continuous and that of port 2 is discontinuous.

Fig. 11 shows the waveforms of the converter operating in buck-mode just before switching to phase-shift mode at time of 39ms. Here, the output voltages have nearly stabilized and the currents reduced significantly in magnitude. In this case the source converter is only providing current for the attached loads and not for charging the output capacitors. Therefore, the waveforms of the currents i_1 and i_2 are similar.

The time t_1 (see Fig.9) can be adjusted to control the ramp rate of the phase angle during the buck mode and this limits the peak current occurring in the source converter. An alternative method is to set the effective duty cycle to 50% and let the source converter operate continuously in current limit, at the maximum allowable current level, until sufficient voltage is on the load side of the converter and the current begins to reduce. By operating in current limit the start-up time of the converter would be reduced although higher currents would flow.

In the second time interval, the power supply is operating in phase-shift control mode. There is no boost operation between the buck mode and phase-shift control mode in this example. At the beginning of this interval, both phase-shift angles of each converter increase linearly to realize a soft start action. In **Fig.12** it can be seen that the phase angle ϕ_1 is greater than ϕ_2 since the capacitance C_1 required more current to charge. The ratio of ϕ_1 to ϕ_2 should be kept even if the values of ϕ_1 and ϕ_2 are limited in order to be sure that the two loops remain decoupled.

As shown from the simulation results the proposed start-up method of operating the source converter firstly in a buck mode ensures that the load voltages of the other ports can be increased in a controlled manner. Independent phase-shift control of the other port voltages can then occur. Once the port voltages are all being regulated the start-up operation can then switch to the normal operation that allows the independent bi-directional flow of power between all of the converter ports.

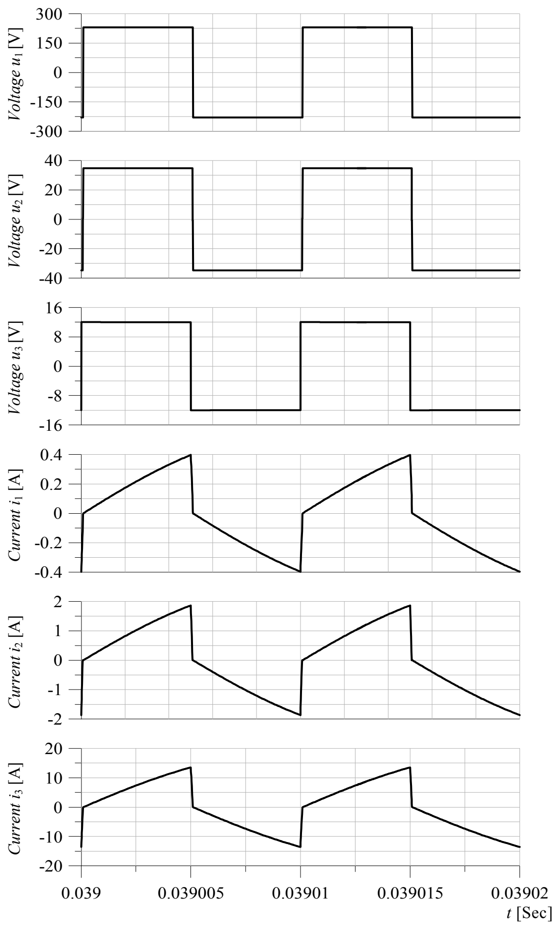

Fig.11: Simulation waveforms of the start-up scheme at t=39ms.

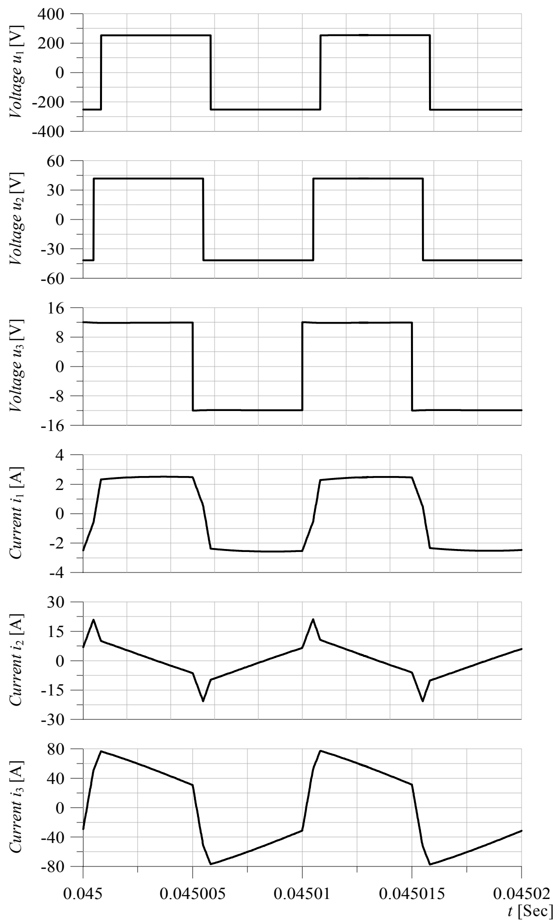

Fig.12: Simulation waveforms of the start-up scheme at t=45ms.

V. CONCLUSION

Future hybrid automobiles will require bi-directional, isolated power flow between voltage networks of widely varying voltages. One power supply type that is able to achieve this full bi-directional power flow between three different voltage networks is the three-port power converter. The three-port converter system uses a high-frequency transformer with three windings that is connected to a full-bridge converter on each winding or port. The control of the power flow between the ports is via the phase-shift control of the individual full-bridge converters operating in square-wave mode.

In the automotive application, a single power source will be typically available to power up all the voltage networks and normal phase-shift control can not be used to start-up the converter system. A start-up method has been presented in which the converter can be operated in a buck-mode, followed by a voltage boosting mode until sufficient voltage is present to enable phase-shift control. Detailed analysis of the buck and boost operation during start-up is presented and a control method to limit the current during start-up is described. Simulation results show that the proposed start-up method operates as expected.

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