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Superconductor Application to Relieve Voltage Collapse in Synchronous Boost DC-DC Converters

Fuel cells are the most appropriate power suppliers for mobile and portable minute electronic devices, yet they provide intrinsically low power source in practice. As a consequence, influential equipment which can improve output voltage of fuel cells is synchronous DC-DC boost converter. However, voltage collapse is the major drawback in this type of converters, and it occurs when load power increases substantially. Increase of current throughout the region of Mass Transport polarization of fuel cells appears as a dramatic voltage drop in the both fuel cell and converter, and this current yields a low output voltage. Accordingly, MOSFET switches of the converters would not be driven by the low output voltage, and voltage collapse appears. In this paper, it is devised that use of superconductor technology can limit the increased current and alleviate voltage collapse in synchronous converters. Hence it is introduced as a novel potential concept of superconductor application. To satisfy the Authors' aim, the superconductor is installed in series with the load after the node in which output voltage is sampled in order to derive MOSFETs by the controller circuit. By tuning the operation current of the superconductor in the value corresponding with the beginning point of the Mass Transport region of polarization curve, superconductor would be able to halt the current and cease voltage collapse.

Keywords: Collapse, Fuel cell, Low power converter, Synchronous boost converter, Superconducting fault current limiter.

1. Introduction

Negative effects on environment, high priced equipment utilized for exploiting, and being unreliable as a constant source of energy are all drawbacks of fossil fuels. Accordingly, researchers have been investigating alternative sources such as solar, wave, wind, and fuel cell energies. However, each of possible alternative options brings about new discussions. As a case in point, wind energy used to rotate turbines to produce electricity exhibits randomly manner related to its velocity. Therefore, in addition to studies toward promoting mechanical structure of the wind turbines, investigations must be directed to boost the power quality required from the electricity produced by wind turbine-generation set [1].

The other widespread trend is using mobile and minute electronic devices like cell phones, calculators, tabs, portable media systems, and so forth. In these cases, fuel cells are widely used due to their light weight and compatibility, although some modifications should be devised for electric circuits applied to such fuel cell-fed minuscule appliances [2]. In fact, fuel cells typically yield a low voltage, usually with peak voltage less than 1 V for no-load and around 0.4 V for full load conditions. It is undeniable that this low voltage results in a very low power not being suitable for practical purposes. Therefore, potential solutions have been investigated by the researchers to adapt low power fuel cells and other low power resources such as thermoelectric devices to practical tools and devices [1]-[4].

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DC-DC converters are the remarkable and convenient solutions to adapt the low output power of fuel cells to running portable and tiny electronic devices. Since low power converters would be triggered by a low input voltage, it is reasonable to use low power converters to harvest the energy as high as possible from fuel cells. Because of this eye catching characteristic of low power converters, they have being been the chief point of attention for recent years. The most major and principal topologies of low power converters are Boost, Buck-Boost, and Flyback configurations which can be potentially manipulated for sensible applications. Besides these topologies, many others configurations have been suggested for low voltage applications [5]-[8]. The results would be immensely practical in low-power-fed circuits in mobile and portable electronic devices and sensors which are mentioned in [9]. One of the major concerns of the low power converters is their internal droop voltage which is relieved by advent of synchronous converters which are attractive to designers. Why synchronous type is the central concentration of design is to minimize loss in low power circuits. One of the main approaches for reduction of the conduction loss related to conventional boost converter is using high frequency switching. MOSFET is the best option for high frequency switching applications, but it has a body diode which would waste considerable power if the switch is not triggered timely. Providing a timely-switching by an external source for the driver of the converter is too complicated because operation conditions of the converter should be continuously considered for an optimal switching. However, if the driver (regulator) is supplied by the output node voltage of the converter, the complicated regulators would be abandoned, and more simple circuit can be considered. Although, using synchronous converter simplifies the control circuit design, it may reveal the other disadvantage which is voltage collapse. When output voltage, used as synchronous voltage by the regulator, is decreased below a certain value, the driving circuit and consequently the converter would be turned off, and voltage collapse would arise. The phenomenon generally occurs when current of the converter increases, dramatically in the Mass Transport operation region of fuel cell’s polarization curve, and voltage drop through the converter and other circuit elements increases. It is worthy to mention, voltage collapse concept in Boost Converters is likely a new topic for exploring, though it has been appears with low power source applications. This controversial issue was elaborately addressed by [10], in addition to start up circuit, and an analytical approach was though up in order to predict the voltage collapse.

The fact that increasing current is the most influential factor, propelling the circuit into voltage collapse, induces the idea that using a method to confine current especially when increasing load makes fuel cell work in Mass Transport region of polarization curve can eliminate voltage collapse from synchronous boost converters.

A large amount of researches has been done on application of superconductors in AC [11], [12] and DC circuits [13]-[15], that they are known as Superconductor Fault Current Limiters (SFCL). In fact, the most attractive characteristic of SFCLs is their definitely different behaviors under normal and fault current conditions. This behavior may be described as following: under normal current condition, superconductor is just like an ideal conductor having impedance equal to zero, while during the fault condition that current exceeds a certain value, superconductor behavior converts into the impedance showing considerable resistance which suppresses the fault current. In view of the two opposite aspects of SFCLs, Authors here develop the idea of superconductor application into suppressing the voltage collapse in low power synchronous DC/DC converters which are used to boost Fuel Cells' low output voltage. In this way, when fuel cell is supplying the circuit, and it is in the last zone of V-I characteristic, superconductor can obstruct the current and consequently diminish voltage drop through the circuit. As a result, output voltage which is utilized to derive converter switches would not decrease and continue driving DC/DC converter. Indeed, this would be an obstruction preventing voltage collapse.

The paper is structured as following: Voltage Collapse is investigated in section 2, the proposed idea of this paper is developed in section 3, superconductor modeling is described in the following section, simulation results confirming the effectiveness of the proposed methods is discussed in section 4, and the last section presents the conclusion of the preceding sections.

2. Voltage Collapse

Voltage collapse phenomenon may be observed not only in power systems, but also in synchronous boost converters which are the focus of the current research paper. In power networks, voltage instability may initiates in a bus. In this case, the slope of voltage is in opposition with the reactive power. Spreading voltage instability in a wide area of the system can lead to voltage collapse in which voltage profile decreases significantly in power system [16]. Indeed, voltage collapse imposes Blackout on the system, and as it is unanimously accepted, reconstructing of a collapsed system dictate too costs to the planners and investigators.

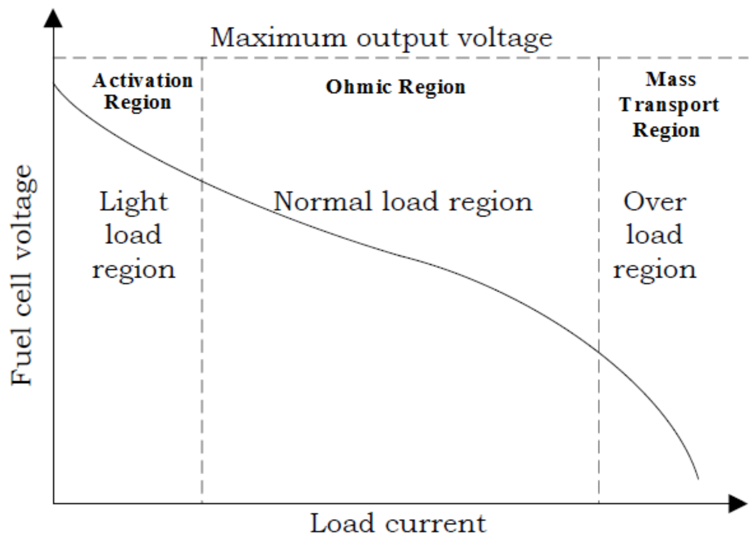

Fig.1. Polarization curve of fuel cell

In boost converters, blocking voltage collapse is important since staring up the switches is a controversial issue in synchronous boost converters. Thus, if voltage collapse happens, converters should be started up again, and it is not desired by the designers. Voltage collapse scenario is a bit different in synchronous boost converters, particularly ones boost voltage in the circuits supplied by low-power fuel cells, in comparison to bulk power systems. As it is known, V-I characteristic of fuel cell called polarization curve (Fig. 1) has three regions defining the operation mode of the cell. . During the first region which is

Activation Region, voltage drop is due to the activation over potential which arises from the kinetic of charge Transport reactions across interfaces. This period also longs through a short duration. The next region representing a pseudo linear behavior as the current density increases is called Ohmic Region in which voltage decrease is imposed by the internal resistance of the cell itself. Finally, Mass Transport losses region appears. This period results from limited supply of reactance to the electrodes by sluggish Mass Transport process. During this period, current density increases sharply while voltage decline rapidly.
Taking the behavior of fuel cells introduced by polarization curve into account, when demand power increases, fuel cell compensates the load by excessive current in the third operation region, Mass Transport. Accordingly, the considerable value of current produces influential voltage drop not only in fuel cell, but also through the resistances of inductor and MOSFET switches. As the first result, the output voltage by which the MOSFET switches are driven diminishes (Vsample in Fig. 2). The declined voltage would not be able to turn MOSFETs on and off, and consequently the boost converter breaks down.

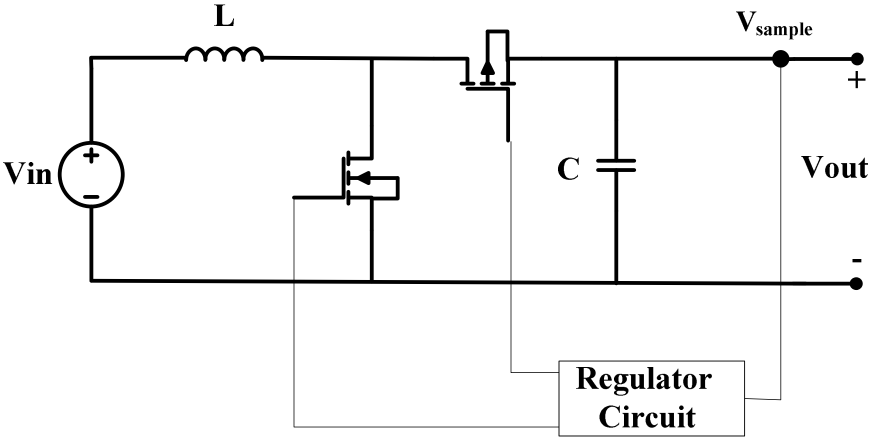

Fig.2. Circuit diagram of a DC-DC boot converter

Besides the theoretical description of the phenomenon, voltage collapse was formulized by [10], and the authors analytically demonstrated the relationship between voltage collapse and the current of the circuit. Then, the authors in [8] clarified this relationship in Buck-Boost and Flyback type converters. To become profoundly aware of the phenomenon, a brief explanation of the relationship in [10] is presented here.

Considering Figure 2, during the continuous conduction mode, I_{in} passes through the resistances of the inductance, one of the MOSFETs, and circuit board traces. The power which is lost in this case can be shown as RI_{in}. In other words, an equal resistance R is the representative of the total resistance of the mentioned elements. Besides that, another part of the power would be dissipated in the resistance of the capacitor shown by r_C. Since the squared rms capacitor current is:

$$I_C{}^2 = I_{out}(I_{in} - I_{out}) \tag{1}$$

The lost power in capacitor, P_C, would be:

$$P_C = I_C r_C{}^2 \tag{2}$$

In addition to resistive power loss in equivalent resistance (R) and capacitor, MOSFETs squander a portion of power in transition from on state to off state, and vice versa. This wasted power depends on the switching frequency, off state voltage (V_{off}), and on state current (I_{on}). Therefore, it can be shown by:

$$P_{switching} = fV_{off} t_{switch} I_{in} \tag{3}$$

$$P_{switching} = KI_{in}, K = fV_{off} t_{switch} I_{in} \tag{4}$$

Now, the power balance equation, shown below, is elicited

$$V_{in} I_{in} = P + KI_{in} + RI_{in}^2 + r_C I_C^2 + P_{oh} \tag{5}$$

It is worthy to prompt that control circuits also consume power to derive the switches. Therefore, their consumption is taken into account in the power balance equation by P_{oh}.

In reality, all parameters, except I_{in}, are considered given. It means that if the equation would be solved to attain I_{in}, it would be obvious that the voltage collapse occurs while the roots obtained for I_{in} are complex. This happens when demand is too high and the dissipation of power dramatically soars.

3. The Proposed Idea

Focusing on the most influential factor, which is excessive current, in voltage collapse, it is decided that if there is a current limiter which is activated when the condition is a stimulus to voltage collapse, the event would be obstructed. One of the most practical such current limiters are SFCLs, which its application in power systems have been profoundly studied by researchers. SFCLs behave exactly like a zero resistance while the current flowing through the system is within the normal range. Nonetheless, their function inherently is changed into a high resistance as the current exceeds a certain value. This characteristic is exceptionally practical in the case of voltage collapse in synchronous boost converters. However, taking into consideration what the researches have been done on the application of superconductor in low-power low-voltage DC circuits [17], [18], Thin Film Superconductors would be applicable in our purpose.

Utilization of a thin film superconductor with appropriate dimensions can represent the characteristics of an ideal current limiter in boost converters. In other words, while the demand power holds the values which keep the converter in correct conditions to boost the voltage, superconductor shows the characteristic of a zero resistance, and no dissipation would appear through the superconductor. On the other hand, as the load request increases, fuel cell approaches its Mass Transport operating region to meet the load demand, so superconductor initiate its quenching behavior and confine the current to alleviate voltage drop through the circuit. Apparently, voltage collapse does not emerge in this condition, and the converter would be still driven by the voltage which is sampled on the output side of the circuit.

The most important issue is the dimensions of the superconductor which is utilized in the circuit. It should be chosen in a way that the quenching behavior of the superconductor initiates when the current is near the value which propels the converter toward the collapse state. During the nonzero-resistance behavior of the superconductor, the currents would be kept within the value being higher the normal current but smaller than the critical amount. This guarantees that voltage collapse do not appear even if the load demand is too high.

It is worthy to mention that the superconductor should be installed before the load and after the node which its voltage is sampled to drive the converter (Fig. 3). If the superconductor is considered before the mentioned node, the voltage drop through the superconductor leads to more voltage drop on the node driving the converter. This also happens if it is set up after the fuel cell and before the converter. That is, the practical location for superconductor is after the node used to drive the converter and before the load.

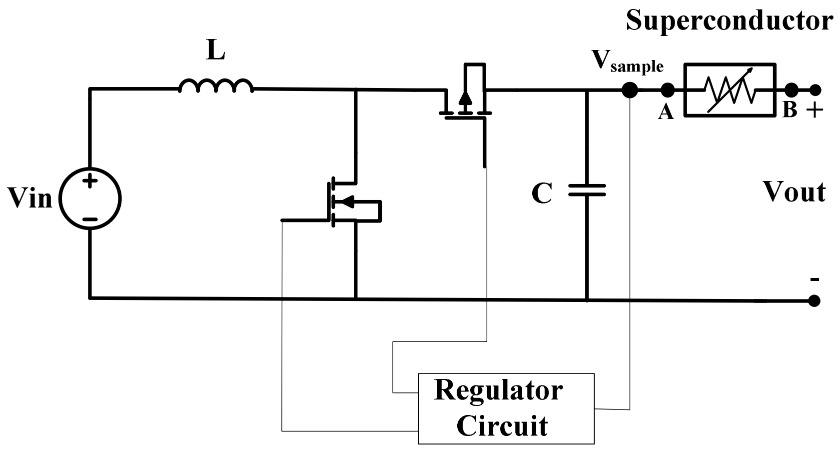

Fig.3. Proposed scheme for low-power converters

4. Superconductor Modeling

In order to prove the functional effect of superconductor on suppressing voltage collapse in low-power converters in the following section, here the associated equation of superconductor is introduced. The equation which is used in [13] is described as follow:

$$R_{SFCL}(t) = \begin{cases} 0 & t_0 > t \\ R_m[1 - e^{(-\frac{t-t_0}{T_{SC}})}]^{0.5} & t_0 < t < t_1 \\ a_1(t - t_1) + b_1 & t_1 < t < t_2 \\ a_2(t - t_2) + b_2 & t_2 < t \end{cases} \quad (6)$$

In which, R_m is the maximum resistance indicated by the superconductor, and t_0 is the time at which current exceeds a certain value, and quenching behavior of superconductor begins. T_{sc} is the time constant during which superconductor changes its state from non-zero to maximum resistance mode. After excessive current is cleared, the superconductor characteristic recovers through two linear periods designated by t_1 and t_2. a_1, a_2, b_1, and b_2 are constant values which are used in linear equations of recovery behavior of superconductor.

Equation (6) is profitable for implementation of superconductor model in the software to simulate the proposed idea presented in the previous section. The block representing superconductor model executes the following procedure: firstly, measured output current of the converter is considered as an input data, and it is compared with the critical current set-point. If the measured current is less than the critical value, an output signal carrying zero value would be produced. On the other hand, if the measured current is greater than the critical set-point, the exponential equation displaying quenching behavior of the superconductor is triggered. Thus, the output signal possessing the value obtained from the exponential part of equation (6) is created. Then, the output signal is considered as an input signal for the Controlled Voltage Source. The voltage source yields a voltage which is obtained from multiplying the output signal of the first step by the measured current. That is, the produced voltage plays the role of voltage drop across the superconductor. If the measured current goes down below the set-point, recovery period is triggered, and the third and last parts of equation (6) produce the resistance of superconductor according to their constant times, t_1 and t_2, consecutively. Figure 4 shows the diagram of the procedure which models superconductor. Both node A and node B are connected in series to sample the output current and function as the superconductor voltage, respectively.

5. Simulation Results

In this section, the proposed idea of preventing voltage collapse in low-power converters by means of thin film superconductors is simulated using MATLAB/SIMULINK package software. In order to approach to the factual results, the elements used in setting up a low-power converter supplied by a low-power FC are chosen, presented in Table 1.

Table 1: The converter parameters

Symbol	*Quantity*
L	10 μH , 10 mΩ
R_{MOSFET}	4 mΩ
C	250 μF, 13 mΩ
f_s	200 kHz
C_r	220 μF
P_{FC}	P_{Max}=2.5 W, P_n=1.5 W

In the simulation, fuel cell supplies a 1 W load. In 0.008 sec, the load power value increases suddenly to about 3 W. accordingly, during the first period which load power is near the nominal power, boost Converter is driven by the control circuit and improves the voltage level. However, after the change of the load up to nearly 3 W, fuel cell has to increase its current so that the load demand would be compensated. Therefore, voltage drop occurs not only on the end-terminals of the fuel cell, but it is observed also through the circuit elements such as the inductance and the MOSFETs. This would result in a decline in output voltage which is used to trigger MOSFETs. As the output voltage is not high enough to switch MOSFETs, the converter would break down, and voltage collapse happens. The results showing this phenomenon are displayed in figures 5-7. As it is clear in the figure 4, at 0.008 sec which load increases by 3 W, voltages on the both sides of converter, source and load sides, decline down to zero for converter's switches are not driven by the output voltage and through the regulator circuit.

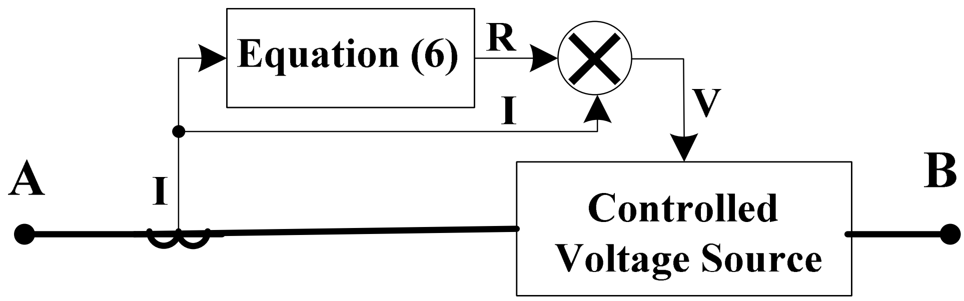

Fig.4. Block diagram of the superconductor Model

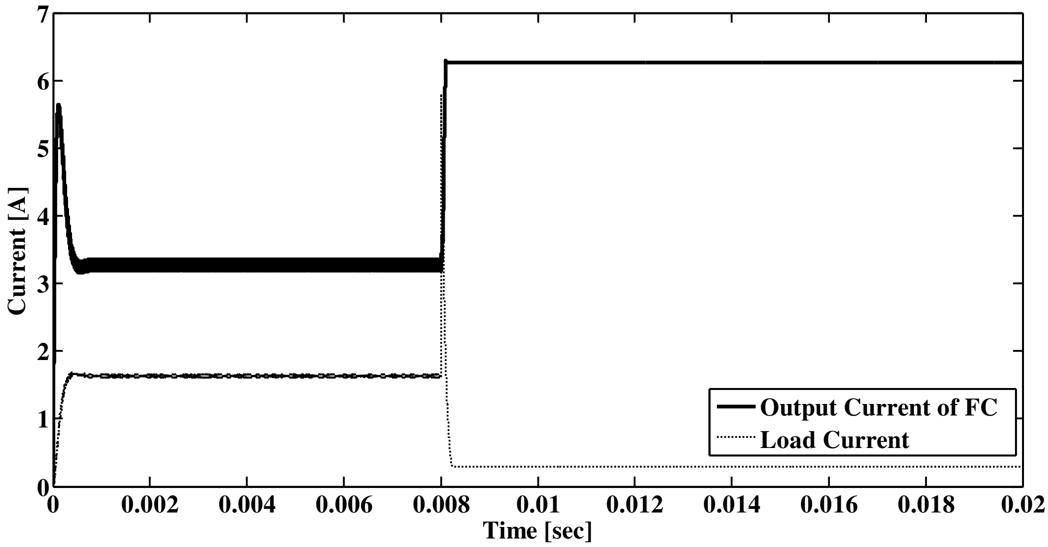

Fig.5. FC current and load current- without superconductor

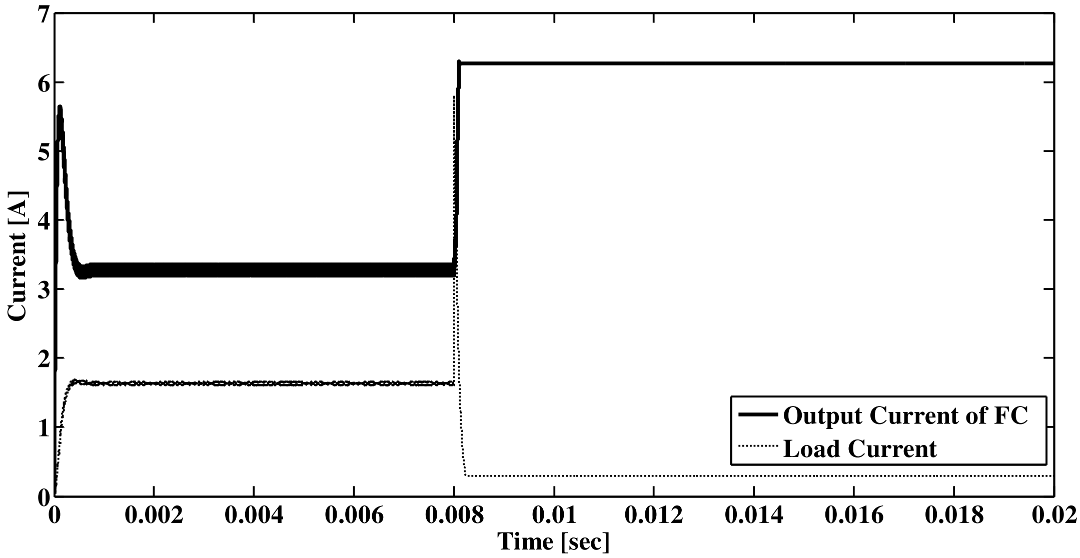

Fig.6. FC current and load current- without superconductor

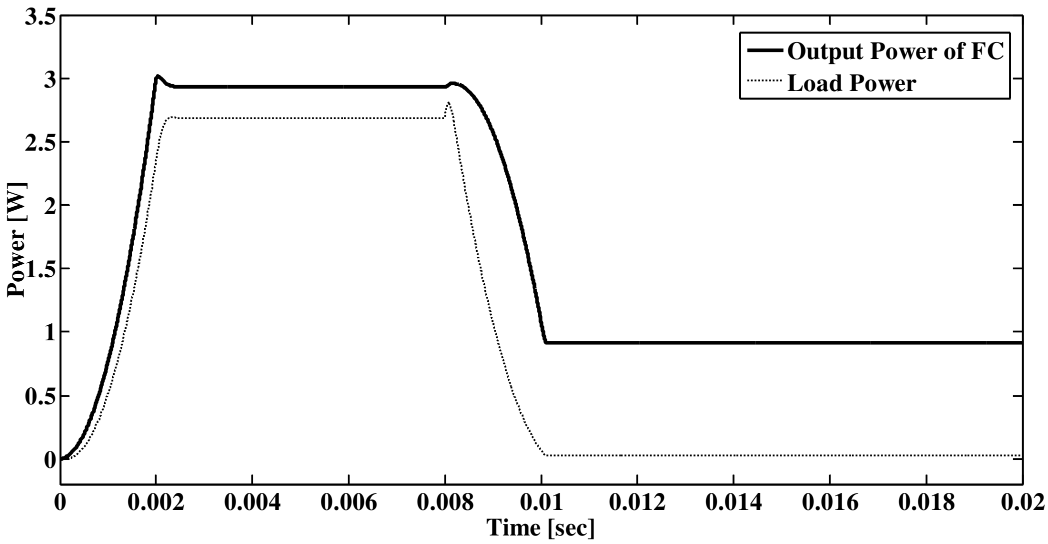

Fig.7. FC power and load power- without superconductor

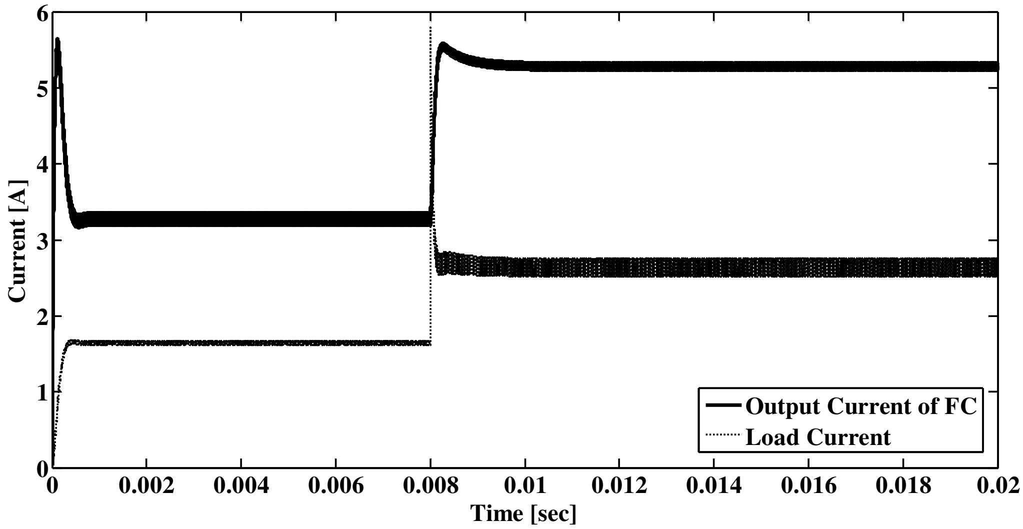

Fig.8. FC current and load current- with superconductor

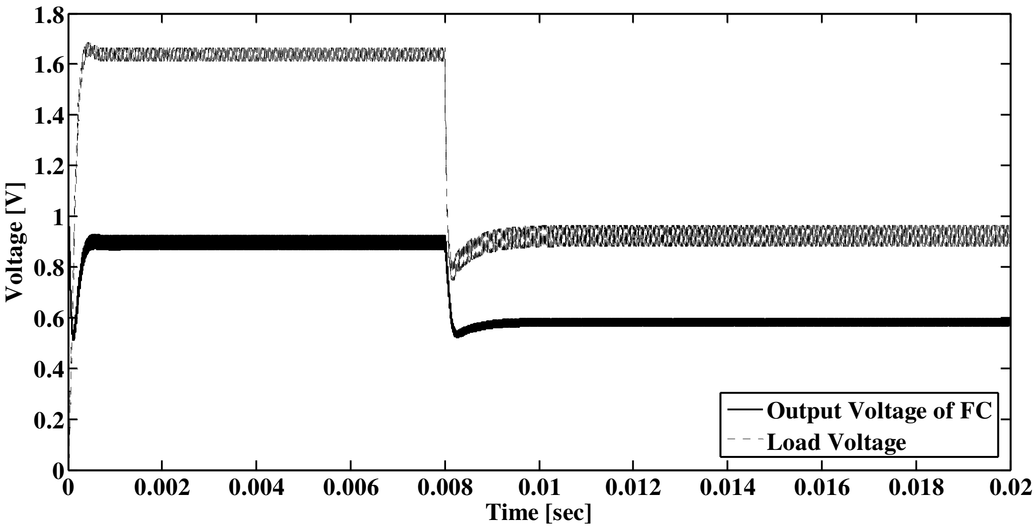

Fig.9. FC voltage and load voltage- with superconductor

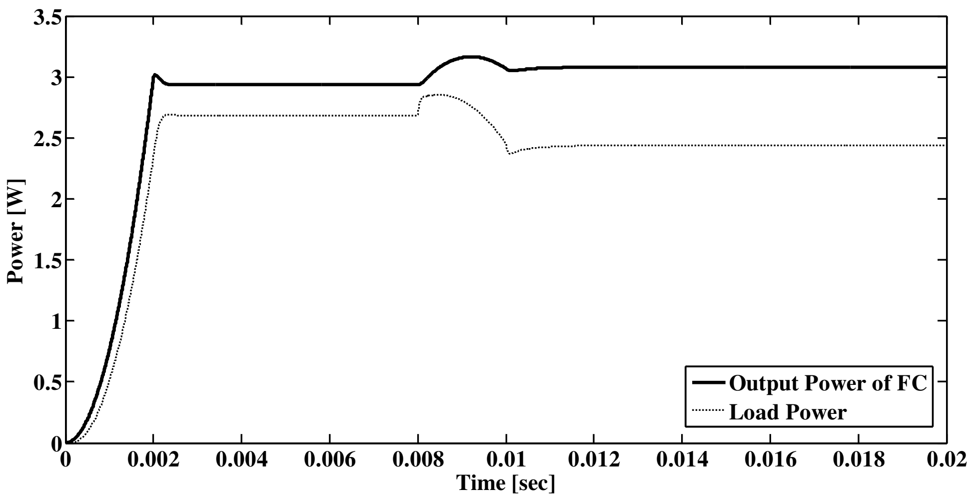

Fig.10. FC power and load power- with superconductor

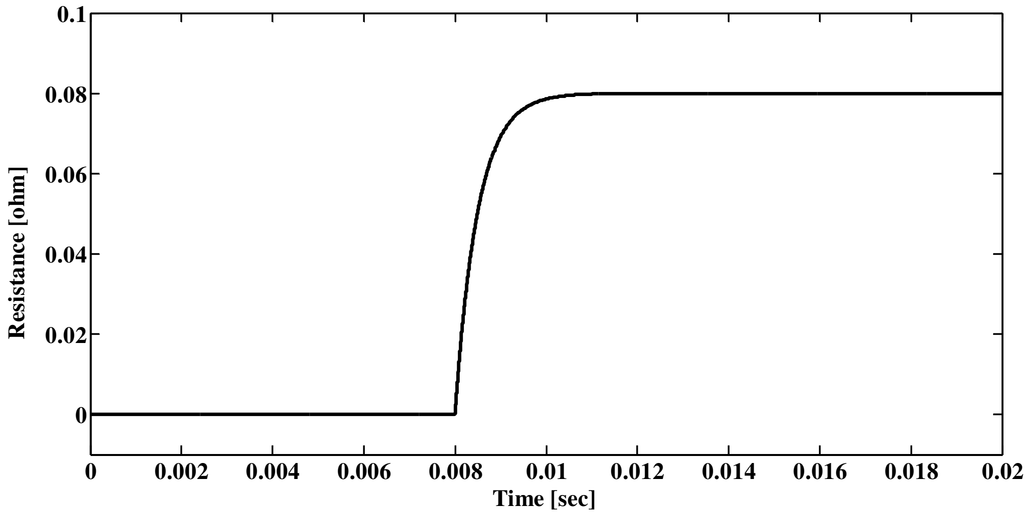

Fig.11. Superconductor resistance

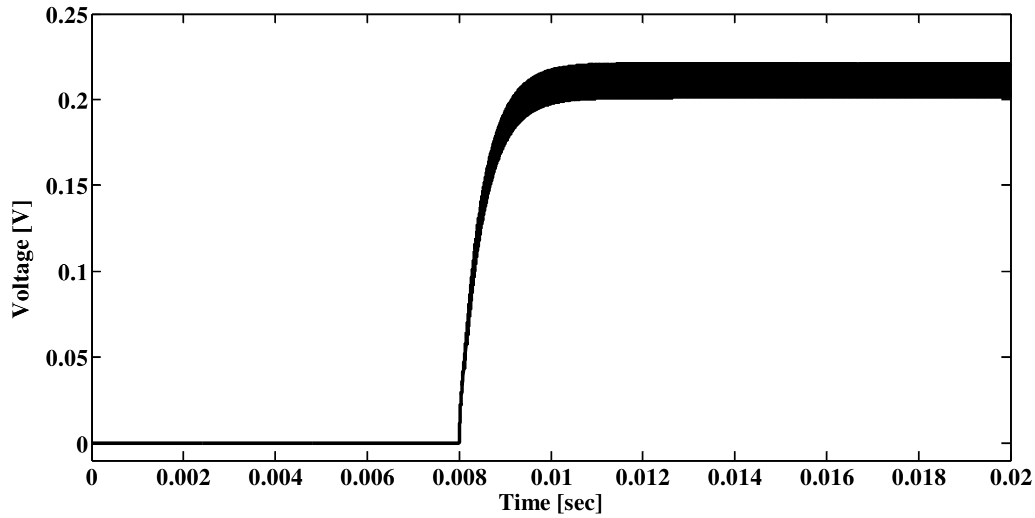

Fig.12. Superconductor voltage

On the other hand, taking into account the behavior of thin film superconductor, simulation is repeated again with a modeled superconductor. Since the load power increases from 1 watt to 3 watt at 0.008 sec, the current rises sharply and leads to dramatic voltage drop. However, the superconductor restricts the increasing current to certain value which depends on the maximum resistance value of the superconductor. This would halt the voltage collapse, and low-power converter would continue its function. Figures 8-10 displays the results obtained from the simulation in presence of the superconductor. Moreover, figures 11 and 12 depict the behavior of superconductor through the simulation.

6. Conclusion

In this paper a novel concept is introduced for superconductor application in low power converters. It is discussed that fuel cell-fed low power circuits used for portable electronic devices encounter voltage collapse when power demand increases in such a way that propel fuel cell to operate in Mass Transport region of polarization curve. According to the fact that increasing current is the key factor in voltage collapse phenomenon, using a current limiter can successfully prevent voltage collapse. The current limiter should have zero resistance during normal operation so that no dissipation appears in low power circuit. Taking into account the mentioned criterion, the most practical current limiter is thin film superconductor whose behavior is similar to a zero resistance in normal conditions, but it presents a resistive behavior when the current exceeds a certain value. The proposed perceptive idea of the Authors is proved through the simulation of a low power circuit supplied by a fuel cell. Also, the superconductor behavior is modeled in the software so that a comprehensive investigation would be done. The simulation results declare the proposed concept of suppressing voltage collapse by superconductors is influentially effective.

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