

Load Dump Analysis in a 42/14V DC-DC Converter for Automotive Applications

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Abstract

The paper presents a model for a dc-dc centralised based architecture using Matlab/Simulink for load dump analysis. As the electrical load varies for various driving conditions such as day or night, summer or winter; and city or country side, the analysis of load change is a very important parameter for system behaviour. In order to study the 42V power generation dynamic performance under load variations, step change in loads have been investigated. A detailed mathematical model for a 3-phase, 4 kW and 42V Lundell alternator average electrical equivalent circuit along with the DC/DC converter based architectures for dual-voltage systems has been covered in previous publications. Aspects of the steady-state output current capabilities, transient behaviour due to load dump on the 14/42V buses and the behaviour of the system model under different loads are assessed and results discussed. The performance of the 42V Lundell alternator with the interleaved six-phase buck dc-to-dc converter system is modelled using Simulink software to assess the effectiveness of the model and its transient behaviour. The simulated results are presented for the transient characteristics of the system for load dumps.

Keywords: 42V PowerNet, automotive, DC-DC converters, dual system, load dump, transient.

1. Introduction

Growing concerns about public health, global warming and economic safety are calling for sustainable road transport technologies. Road transport contributes about one-fifth of the EU's total emissions of carbon dioxide (CO₂), the main greenhouse gas. While emissions from other sectors are generally falling, those from road transport have continued to increase since 1990. Passenger cars alone are responsible for around 12% of total EU emissions of carbon dioxide (CO₂) [1].

More recently, a European white paper 2011[2], adopted a roadmap of 40 concrete initiatives for the next decade to build a competitive transport system that will increase mobility, remove major barriers in key areas and fuel growth and employment. At the same time, the proposals will dramatically reduce Europe's dependence on imported oil and cut carbon emissions in Transport by 60% by 2050 [2]. One of its key goals is no more conventionally-fuelled cars in the cities.

A special Euro-barometer survey, Brussels, 07 October 2011[3], found that more than two Europeans in three see climate change as a very serious problem and almost 80% consider that taking action to combat that it can boost the economy and jobs. In addition, taking into account that in Europe 73% of all oil is consumed by transport, the introduction of Electrical Vehicles (EVs) should be a first priority for savings of the most critical source of primary energy. Electric

vehicles (EVs), due to their zero local and potentially minor greenhouse gas emissions, are considered the cleanest option and provide opportunities in terms of efficiency and flexibility in the use of energy. The mass use of EVs however is currently facing several weaknesses amongst which are: limited driving range, high cost and overall limited efficiency.

The current 14V bus and Lundell based alternators are being pushed to the limits to meet the higher demand from current luxury cars and this will be further stretched moving to a fully electrical car. Industry consortia such as SICAN in Europe and MIT in the USA propose that a 42V or higher voltage bus system for next generation cars is a must. A 42 V system would offer far greater power availability to the vehicle electrical system and enable many of the traditional mechanical and hydraulic systems to be electrically driven. Moreover, the current drawn from the battery will be lower and the possibility to implement additional safety and comfort features. In addition, nearly all accessory systems present in today's vehicles are candidates for electrical conversion. These include a variety of pumps, blowers, and actuators that can benefit from the introduction of variable-speed motor drives.

The power semiconductor devices, converters/inverters, control and switching strategies, packaging of the individual units, and the system integration play a major role in bringing hybrid and fuel cell vehicles to market with reliability and affordability. The power electronic system should be efficient to improve the range and performance of the electric vehicles, and fuel economy in hybrid vehicles. In addition to the power devices and controllers, there are several other components such as capacitors, inductors, bus bars, thermal system, etc., which form a major portion of the power electronics unit. The packaging of all these units as one system has significant challenges.

Unfortunately, economic and technical considerations do not allow an easy transition to a single 42V Power-Net and the abandonment of the 14V systems to history. Therefore, in the medium to long term most car manufactures will provide cars with dual voltage systems (42V-14V), where the 42V power distribution systems will co-exist with the traditional 14V electrical system in the same vehicle. In this way, the dual-voltage system provides a smooth transition period for loads to migrate to the single 42V system architecture.

The 42V/14V dc dual-voltage supply centralised architecture system model with a single battery has been carried out in detail by the author [4]. The system model is composed of a 42V Lundell alternator configured as a three-phase three-wire star connected wound-field synchronous machine followed by an uncontrolled six-phase rectifier to generate the required 42V. The 42V dc output terminal voltage is used to supply the 36V energy storage battery and the associated high power loads. The maximum electrical power capability of the alternator is limited to 4kW to meet the requirements of future automotive loads, safety, comfort/convenience, driving pleasure and reduced emission. Detailed analysis and simplified averaged models for synchronous machines and three-phase rectifiers with constant-voltage loads as well as the development of Simulink model is presented in [5]. The alternator output dc voltage is further processed by interleaved six-phase dc-to-dc buck converter system operating in the Discontinuous Conduction Mode (DCM) with voltage mode PWM and PID control to supply the desired low-power load with power capability limited to 1kW. The modeling, analysis, control and the development of Simulink model for this sub-system is carried out in [4]

The nominal operating voltages, for the 42/14V dual voltage supply centralised architecture, are 14V and 42V for the two power systems. The maximum operating voltage for the 42V Power-Net system to be supplied by the generator is specified as 52V (including ripples) and a dynamic over voltage of 58V [4]. However, with the high currents and voltages involved, high voltage spikes are a serious problem on the power bus when a fully loaded alternator suddenly loses its load. These voltage spikes, if not suppressed, could exceed hundreds of volt [4] and destroy many electronic components connected to the power bus. Therefore, load dump analysis is a pre-requisite to assess these effects and device overvoltage

protection for the electrical systems from these over voltage transients in order to make power electronic systems more reliable.

2. Load Dump Analysis

Interest in the mitigation of failure effects in automotive power generation systems has been renewed by the prospective use of 42V systems and the fundamental challenges brought on by the newly proposed architectures. Of particular concern are prospective secondary over-stresses of electronic parts resulting from sudden battery cable disconnect, or load dump.

The voltage/current transients due to sudden load removal from the DC bus represent the most onerous aspect of the present automobile electrical system. Load dumps are battery disconnects from the main voltage bus that occur during vehicle operation. Disconnects can occur due to broken wires, loose connections or unwitting maintenance. With the battery and loads disconnected the resulting inductive spikes and alternator output must then be absorbed by the generation stage. Damage from the arc at the point of separation will also occur. Energy dissipated in the arc helps to reduce damage elsewhere confining the voltage level to some 20 volts. Arcing in 14V systems are quickly extinguishable but 42V systems can produce arcs that are long lasting which may lead to a fire hazard.

Because of the possibility of these transients, power semiconductor devices as well as all electronic equipment must be rated at 60V, or about five times of nominal voltage, which is 14V [4-14]. In future automobile electrical systems with the new 42V PowerNet, this transient may be even worse because of its comparably high voltage, which results in a requirement for overrated electronic switches. This may result in the use of power electronic controls of accessories becoming economically unattractive and hence constrain the benefits of the upcoming 42V system. In order to prevent such a trend, the 42V PowerNet has been standardized with tight voltage regulation.

One of the key features of the dual-voltage automotive electrical power system is the extent of voltage regulation required for each of the buses. These limits are presented in Table 1 for each bus along with descriptions for each of the various levels. Such specifications are widely accepted in the automotive industry.

Table1 Dual-voltage electrical power system voltage limits

Electrical system parameter	14V Bus	42V Bus
Battery Voltage	12V	36V
Maximum Dynamic Over-Voltage (Load Dump)	20V	58V
Maximum Static Over-Voltage Including Ripple	16V	52V
Maximum Operating Voltage	14.3V	43V
Nominal Operating Voltage	14V	42V
Minimum Operating Voltage	12V	33V
Power Electronics Voltage Rating	40V-60V	75V-100V

3. System Approach

Laboratory studies of load dump and the secondary failures are costly, and difficult to carry out and repeat. Cost effective computer simulation tools are available to study these failures by executing numerous and exactly repeatable analyses.

The nominal operating voltages are 14V and 42V for the two power systems. The maximum operation voltage for the 42V Power-Net system to be supplied by the generator is specified as 52V (including ripples). The dynamic over voltage is

58V which occurs during the load dump transient, a voltage spike that appears on the power bus when a fully loaded alternator suddenly loses its load. This voltage spike, if not suppressed, could exceed a hundred volts and destroy many of the electronic components connected to the power bus. Therefore, protecting the electrical systems from these over voltage transients is necessary in order to make power electronic systems more reliable.

The breakdown voltage ratings of power electronics in the two systems are significantly higher than the specified maximum operating voltages of the power systems also listed in Table 1. This is because the voltage rating of automotive power electronics is mainly determined by the survivability to commonly encountered transients in automotive, instead of the maximum operating voltages. In addition, a higher safety factor will dictate the use of 75V or even 100V rated components including power MOSFETs and power ICs.

Moreover, the electrical loads such as incandescent lamps will have longer life and higher light output if the applied voltage is regulated to a constant value. Most importantly, reducing the voltage deviations of a distribution bus will be beneficial to reduce the cost of semiconductor switches needed for electrical loads control.

Many automotive manufacturers and suppliers are currently testing new 42V alternator and integrated starter alternator combination prototypes. An efficient application of the proposed design flow can help to analyse the system behaviour before expensive prototypes are tested. A Simulink model developed for a centralised dual voltage automotive electrical power system [4] is a multi-domain simulation package combining circuit, state machine and block diagram simulation. It is based on a unique simulator coupling technology combining the advantages of different modelling abstraction levels with tailor made algorithms for different technical domains. Due to the analytic nature of the design algorithms results are available virtually instantaneously. The user derives a variety of important performance curves and a complete design result.

The generated 42V is further processed by a dc-to-dc buck converter to supply power to the conventional automotive loads expected to remain at low-voltage such as key-off loads, lighting and electronic control units (ECU). One possible way to control the dc bus voltages is to regulate the alternator field current for the 42V bus and to use voltage-mode-controlled Pulse Width Modulation (PWM) with a Proportional Integral Derivative (PID) to regulate the 14V dc bus.

The heart of the dc/dc converter based dual-voltage architecture is the converter system. The preferred choice is the 42V/14V DC dual-voltage supply system centralised architecture with a single battery (36V) and is based on the principle that the power processing is achieved by only one dc/dc power module to supply the existing 14V electrical loads. Also it lends itself to a low cost and low weight, solution reducing packaging problems created by the second battery (12V) and also reducing the electromagnetic interference (EMI) generated by power switching devices in the system. However, the removal of the 12V battery does not alter the dynamic operation of the power converter system, but the power of the converter system must supply the power requirement of all the 14V power loads which is approximately 1kW, under the worst-case scenario. In addition, the non-isolated dc/dc converter topology is the most appropriate architecture because the isolation between the 42V and 14V buses is not required in the automotive power net and has the advantage over the transformer-isolation types in terms of design, low volume, weight, and cost.

A complete system simulation model composed of a 4kW/42V power generation system buffered by a 36V battery and a 1kW/14V interleaved six-phase buck converter using Matlab/Simulink is presented to study load dump analysis in the dual-voltage automotive electrical systems.

4. Electrical Load demand on the 42/14V Systems

The extent of electrical loading has increased progressively with the development of the passenger car. The major reasons for the increase are: automotive manufactures are constantly competing for customers who are demanding new features, greater comfort and improved safety. Improved fuel economy, reliability and reduce emission by cars particularly in cities to keep the health of the population and to maintain the ecological equilibrium.

Moreover, a differentiation can be made between constant or continuously operated electrical loads such as, water pump, fuel pump, engine radiator cooler and the transmission oil circulation pumps, long term loads such as, e.g. head lamps, heated rear windows and short-term loads such as turn signals, stop lamp, etc. In addition, the use of some of the electrical loads is seasonal, such as, air conditioners in the summer and seat heating in the winter.

Furthermore, exterior car lighting legislation requires minimal performance and is among the loads that must be powered even under worst-case situations. Safety systems such air bags, belt tensioning, collision warning and night vision systems are low power consumers. These systems are frequently on standby mode and some may never see operation in the life of the vehicle. However, they are mission critical and must be provided with sufficient power under worst-case scenarios. The loads relating to comfort and convenience, such as AC compressor and seat heater fall into the non-essential category. However, braking, safety and power train systems have the highest priority. The infotainment system, the combination of information technology and entertainment, is a system that is normally not considered a large power consumer in the vehicle.

However, if the requested electrical load is small, the fuel consumption needed for it is also small. When the requested electrical load is higher, it causes more fuel consumption. Therefore, the total fuel consumption increases almost proportionally with requested electrical load. Table 2 shows the average power demand of different loads as a proportion of the total power of a vehicle [7]. The grouping of these loads can vary, depending on the class of the car and options.

Table 2 Average power demand of different loads as a proportion of the total power of the vehicle

Load type	Average power demand (%)
Motors	36
Heaters	27
Lamps	13
Solenoids	11
Electronics	4
Generics	9

5. System Model Description

The proposed 42/14V DC dual-voltage supply centralised architecture system model with a single battery is shown in Fig. 1[4]. The system model consists of a 42V Lundell alternator represented as a three-phase three-wire star connected wound-field synchronous machine followed by an uncontrolled six-phase rectifier to generate the required 42V. The 42V dc output terminal voltage is used to supply the 36V energy storage battery and the associated high power loads. The maximum electrical power capability of the alternator is limited to 4kW to meet the requirements of future automobile loads, safety, comfort/convenience, driving pleasure and reduced emissions.

Detailed analysis and simplified averaged models for synchronous machines and three-phase rectifiers with constant-voltage loads as well as the development of a Simulink model were carried out in detail for the purpose of this work. The of 36V energy storage lead-acid battery is modelled as a resistance in series with a voltage source. This linear model is a very

simple model of a very complicated component and such a model has been widely employed for the simulation by many researchers from the field of automotive engineering [4] and found to be satisfactory.

The alternator output dc voltage is further processed by an interleaved six-cell dc/dc converter system operating in the DCM to supply the desired low-power load with power capability limited to 1kW. The control of the 14V dc bus voltage makes use of voltage-mode-controlled Pulse Width Modulation (PWM) with a Proportional-Integral-Derivative (PID).

6. Load dump Analysis of the Complete System

In order to model the power system of the car described in Fig. 1, the alternator, battery, interleaved six-phase buck converter and loads are modelled as a single platform in Matlab/Simulink model. The inductance, L_a , and capacitance, C_a , are used as a low pass filter to reduce the alternator generated ripple current which may result in shortening the battery's lifetime. The battery was connected to a switch to initiate a load dump for the system's transient analysis.

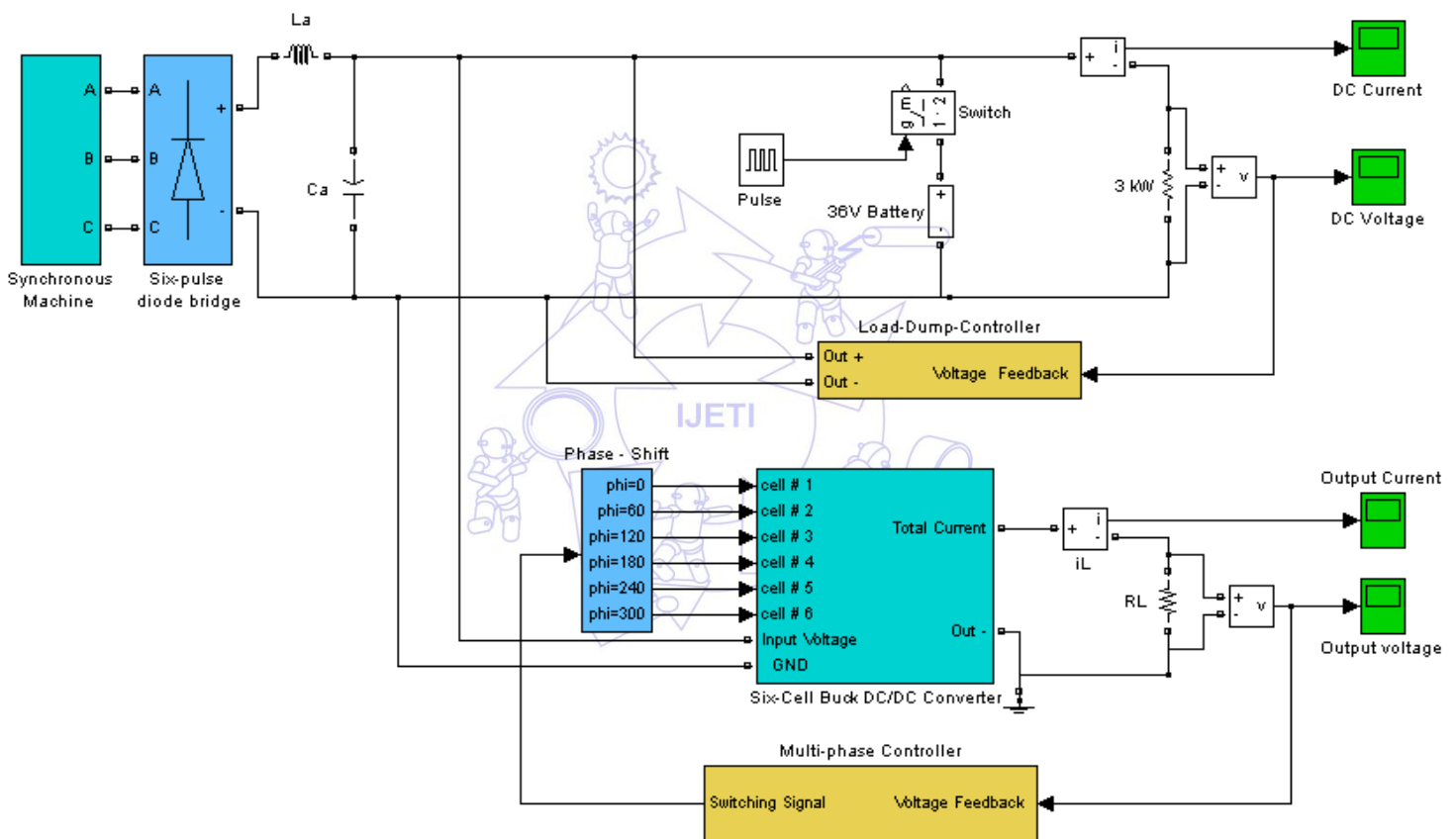


Fig. 1 An implementation of a complete dc/dc converter based architecture with a single battery

In the complete system simulation of Fig. 1, the 42V voltage bus delivers 3kW to various electrical loads such as heaters and high power motors at a steady-state output current of 71A, while the 14V voltage bus for existing 14V loads such as lamps and electronic control units (ECU) delivers a current of 71A at 1kW.

The developed Simulink model of the complete dc/dc converter-based system architecture with single battery is evaluated by performing simulations. To indicate the effectiveness of the developed model, the simulation results for system voltage/current, load dump control, and system response to a step change in the load are validated against the dual/high-voltage automotive electrical power system specification.

6.1. System output voltage and load current

The 42V Power-Net consists of a 4kW alternator and 36V lead-acid battery and delivers 3kW to higher power loads such as heaters and high power motors. The 42V is further processed by the converter system to supply 1kW to the 14V conventional automotive electrical loads expected to remain at low-voltage supply such as key-off loads, lighting and electronic control units (ECU).

Fig. 2 shows the representation of the two buses at different level of voltages and powers using Simulink. The steady-state simulation current drawn by the multiple system buses is very close to 71A. Indicating that the complete system model is able to respond and produce the desired output voltages and required current levels. During the starting up of the system a small peak seen in Fig. 2 is less than the maximum steady-state over voltage (52V) given in Table 1. Moreover, since the transient voltage variations on each bus are very small, the ability to use low cost semiconductors switches to control the various loads is promising.

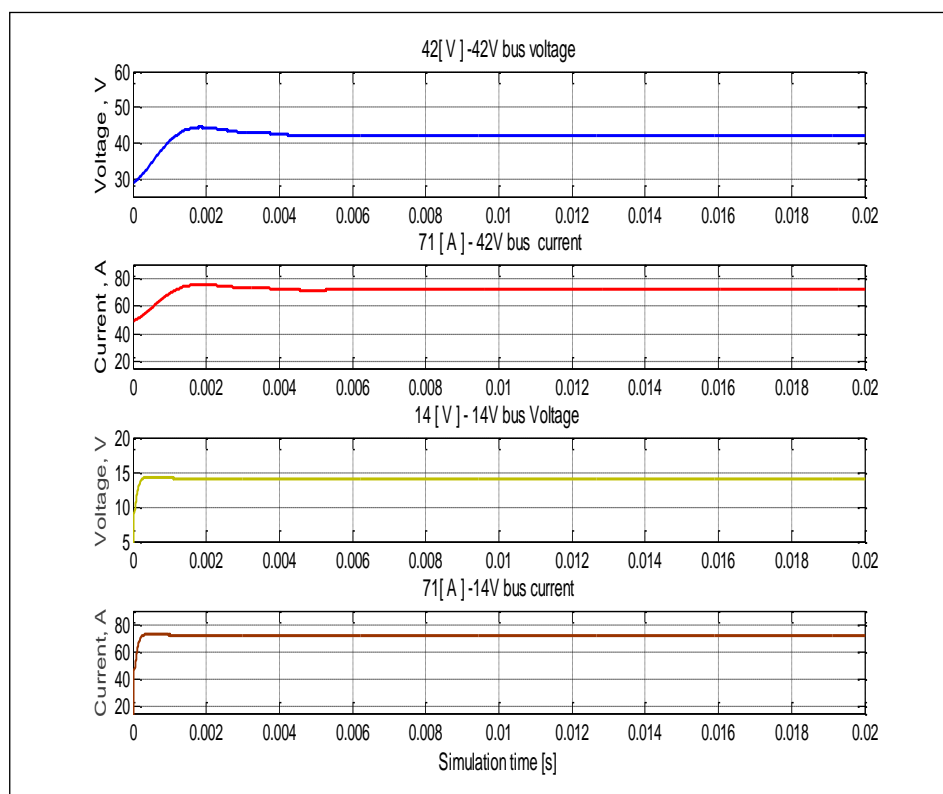


Fig. 2 Voltages and currents of the 42/14V buses

6.2. Load dump analysis

The dynamics of the complete dc/dc converter-based system architecture, that is, the behaviour of the system due to transients is presented. The simulation concentrates on the load dump since it tends to be the worst case scenario transients in the automotive electrical power system. The Simulink model of the complete dc/dc converter-based system architecture in Fig. 1 is used to simulate the load dump transients.

Fig. 3 shows the transient response of the complete system to a load dump on the 42V bus at 6000 rpm (cruising speed). The transient is induced by disconnecting the 36V battery to initiate the load dump transient at time $t=0.01$ s. The peak transient voltage on the 42V bus, Fig. 3, is approximately 54.46V which is less than the 74.8V peak voltage observed with a single voltage system [2]. The reason for the relative stability is due to the 14V loads remaining connected. The 14V bus voltage undershoot is 13.69V and the overshoot is 14.28V. The results show that the performance of the system is stable and behaves well under load dump and the output voltage remains within the desired specified limits presented in Table 1.

The load dump transients can be further suppressed by the use of the load dump controller circuit in Fig. 1. The voltage suppressed by the use of the voltage limiting circuit is shown in Fig. 4. It can be seen that the voltage decreases to 45V on the 42V bus and less overshoot/undershoot on the 14V bus. The small transient voltage variation on each bus leads to the use of low cost semiconductor devices as switches to control the flow of energy to the electrical loads.

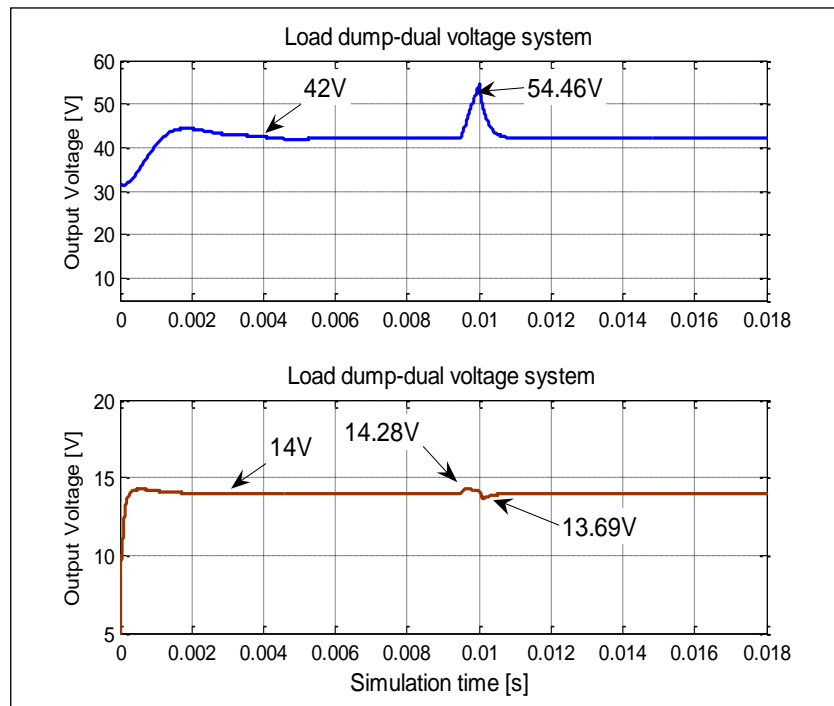


Fig. 3 Dual architecture load dump of 42V system battery

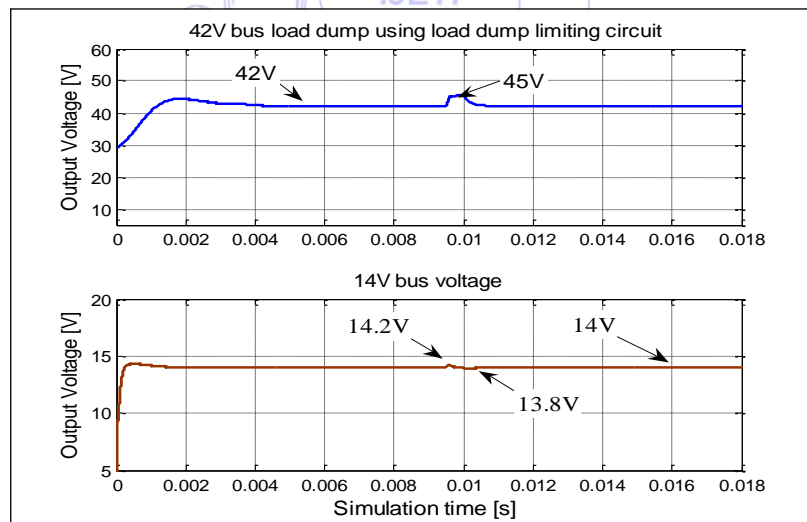


Fig. 4 Dual architecture load dump of 42V battery with voltage limit circuit

7. Response to a Step Change in the Load

Fig. 5 shows the simulation of the dynamic response of the system to a step change in load on the 42V bus at 6000 rpm (cruising speed). The transient is induced by sudden change of the 42V bus load from 50% to 75% and to 100% and then back from 100% to 75% and to 50%. The loading in the 14V bus remains at its nominal value of 71A. The voltage on the 42V bus deviates from its nominal by approximately 3V. This load step change has little effect on the 14V bus; this is

due to the efficient output regulation. The transient voltage deviations observed on the 42V bus in this simulation are within the preliminary voltage limit specifications that were given in Table 1.

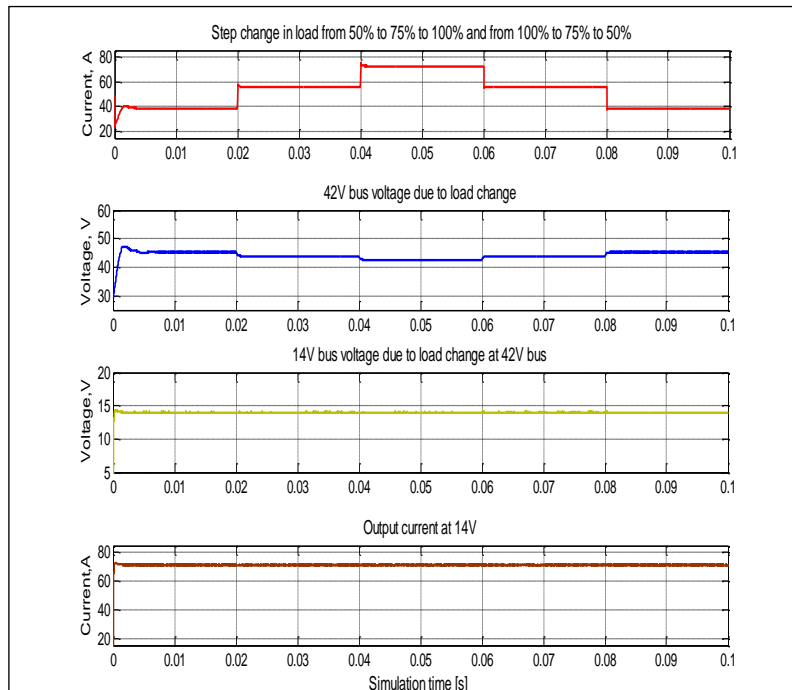


Fig. 5 Dynamic response of the system to step change in load on the 42V voltage bus

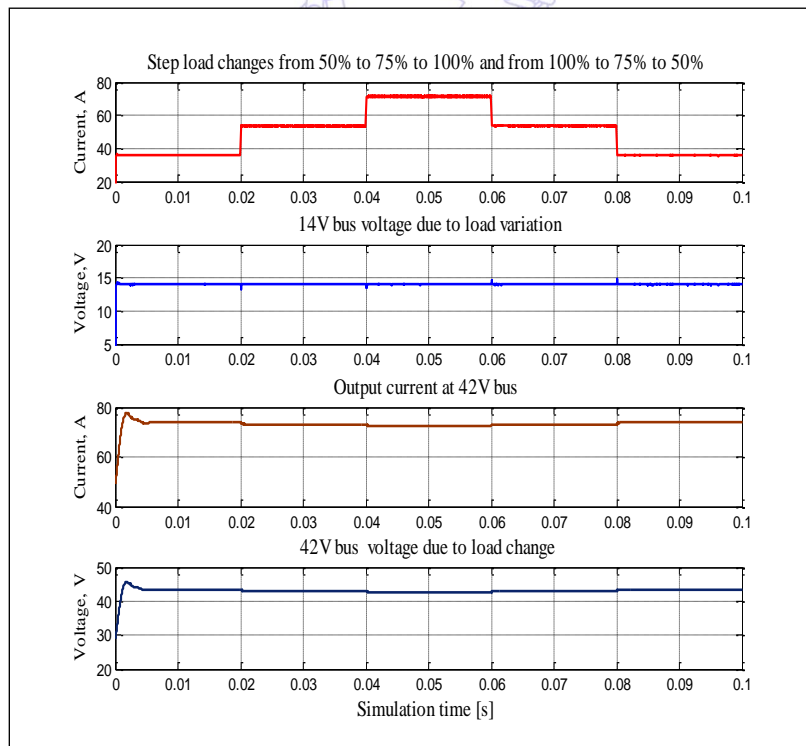


Fig. 6 Dynamic response of the system to step change in load on the 14V voltage bus

The behaviour of the system during the load step change on the 14V bus is shown in Fig. 6 from 50% to 75% and to 100% and then back from 100% to 75% and to 50%. The undershoot is 13.3V while the overshoot is approximately 14.7V. The voltage on the 42V bus with 3kW load also deviates from its nominal by approximately 1V. These transient output voltages remain within the allowable specification reported in Table 1.

8. Conclusions

In this paper, a load dump analysis for a dc-dc based architecture was presented using Matlab/Simulink model. The simulation model used throughout the work permitted to answer a variety of questions including the steady-state output current capabilities, transient behaviour due to load dump on the 42V bus and the response of the system model under different loads. The combinations of both the supply-voltage and load variations that occur in the converter system have been simulated and the results obtained show that the designed system has a low-sensitivity to the load and supply-voltage variations. These variations have only small influence on the output voltage and load current. It can be concluded from the results obtained that the proposed converter can maintain designed output voltage independently of load and supply-voltage variations. It can also be concluded that, this dual voltage automotive electrical system is well regulated and stable under the worst case scenarios.

Due to the interaction between the 42V and 14V systems, the transient suppression is not required. In addition, a low sensitivity to both load and supply-voltage variations is obtained. These variations were small and have no influence on the output voltage and load current and, as such, the specification of the automotive standards were respected. In addition, it offers low sensitivity.

The simulation results demonstrate the high performance features of the dc-dc based architecture system in meeting the future predicated load demand which will lead to reduction in weight and volume of wire harness components as well as fuel saving while complying with the standards regarding dual-voltage electrical power system specifications. It is anticipated that the effectiveness of the whole system proposed here will be of value in future dual-voltage automotive electrical systems.

A 42V/14V centralised system would offer far greater power availability to the vehicle electrical system and enable many of the traditional mechanical and hydraulic systems to be electrically driven. Moreover, the current drawn from the battery will be lower with the possibility to implement additional safety and comfort features.

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