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Design and Analyse of a Parallel Connection Model for Hybrid Energy Systems

Naki Guler[1], Sevki Demirbas[2], Erdal Irmak[2]
[1]*Technical Sciences Vocational School, Gazi University, Ostim, Ankara, Turkey*
[2]*Electrical and Electronics Engineering Department, Faculty of Technology, Gazi University, TR-06500 Ankara, Turkey*
erdal@gazi.edu.tr

***Abstract*—This study proposes a parallel connection method for hybrid renewable energy sources connected on the same bus to obtain an optimum load sharing system among them. Although output voltage of the energy sources connected on the bus changes abruptly, the system continuously adjust the output voltage to a pre-defined constant reference value. Power sharing and voltage fixing operations have been achieved by using PI controllers. The system developed has been simulated for several operating conditions. Simulation results show that the bus voltage are kept constant for all conditions performed and the system reaches steady-state in a very short transient time.**

***Index Terms*—Hybrid power systems, load flow, power system simulation, switching converters.**

I. Introduction

Renewable energy means a type of energy source that is not permanently depleted like sunlight and wind. Especially if there are more than one renewable energy resources operating together, output side of each source is connected in parallel to each other by means of converters [1]. Converters are also used to fix the output voltages of renewable energy resources that operate as interconnected with the grid [2]–[6].

DC/DC converters are electronic devices used for changing DC electrical power efficiently from one voltage level to another. A lot of DC/DC converter topologies operating in buck, boost or buck/boost mode can be found in the literature. Unlike the buck converters boost converters are step-up the output voltage instead of stepping it down. The buck-boost converters can operate either step-down or step-up modes and polarity of output voltage can also be inverted or non-inverted modes depending on converter topology.

Most studies in the literature have focused on either buck converter or boost converter. In this study, as a difference and contribution to recent studies, an effective parallel connection model has been carried out for cuk converters that can operate in both buck and boost modes. Thus, even though the voltage produced by energy sources either increases or decreases instantly, the output voltage remains as stable at a certain level.

In solar energy systems, converter circuits are especially used for regulating the output voltage and DC/AC inverters are used for converting the output voltage from DC to AC [7]–[9]. Voltage regulation systems are required for voltage stability and ensuring the grid conditions in grid interactive renewable energy systems [10]. This operations can be performed on the inverter side or directly on the DC bus. However, DC/AC inverters have more complex switching circuits and control systems as compared with DC/DC converters. Furthermore, usage of a separate inverter circuit for each energy source increases the total cost. Therefore, parallel connection of all energy sources on the same DC bus and realizing the voltage regulation process on this DC bus decreases the cost and makes easy to control operations. Voltage regulation with DC/DC converters is performed by either closed-loop control systems or super-capacitor systems [9], [11], [12].

Another important parameter is the system efficiency in parallel connected systems. In order to increase the efficiency, it is an indispensable requirement that the control of load sharing ratios among the different types of energy sources [13]. Assuming a simple hybrid energy system including two different types of renewable energy sources like solar and wind, the load sharing ratio of each system cannot always be equal. In such cases, some undesired situations may be appeared such as operating the one of energy sources inefficiently and not utilizing from the energy produced by this source. For this reason, load sharing ratio of the each source should be controlled continuously by using current control techniques as presented in this paper.

Rest of the paper organized as follows. Mathematical model of cuk converter is given at Section II and parallel connection model is introduced at Section III. Simulation results of the proposed system are discussed at Section IV. Finally the study is concluded at Section V.

II. Mathematical Modelling of Cuk Converter

According to experimental studies, ripple on the output voltage of a cuk converter is less than the other types of converters; hence, it does not require an external filter on the output side [14]. Due to capability of operating in both buck

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and boost modes, parallel connection of the system is not broken down, even though the difference of the input voltages of the parallel connected cuk converters is very high. Thus, energy usage can be maintained without any interruption. Also, operating the system with high efficiency is possible especially for parallel connected systems.

A simple circuit diagram of the cuk converter is given in Fig. 1, where L_1 operates as an energy storage component on the input side, C_1 operates in both storage and source mode depending on its charge/discharge situation according to switching signals. The converter can be operated either buck mode or boost mode according to duty cycle of switching component. If T_{on} is less than 50 %, the converter operates in buck mode. Otherwise, the converter acts as a boost converter if the duty cycle is higher than 50 %. In both situations, L_2 operates as output source depending on T_{on}/T_{off} time of the switching device. The capacitor C_2 filters the output voltage. Ratio of the output voltage (V_{out}) to the input voltage (V_{in}) is given in (1), where D is duty cycle. As clearly seen in (1), output voltage of the converter is proportional to the duty cycle

$$\frac{V_{out}}{V_{in}} = -\frac{D}{1-D}, \tag{1}$$

Input power of an ideal cuk converter is equal to its output power if the losses are neglected. Accordingly, the relation between the input current (I_{in}) and the output current (I_{out}) can be determined as (2)

$$\frac{I_{out}}{I_{in}} = -\frac{1-D}{D}. \tag{2}$$

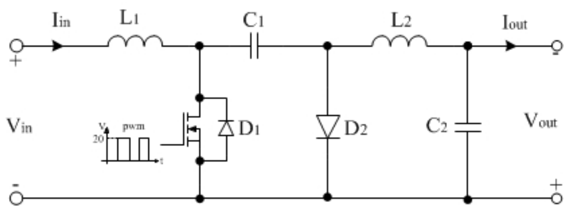


Fig. 1. A simple circuit diagram for cuk converter.

The ripple on the output voltage can be determined as (3), where ΔV_{C1} indicates the ripple on the output voltage, i_{L1} current value of the L_1 inductance, C_1 is capacitance value of the C_1 capacitor, T_s is the switching period

$$\Delta V_{C_1} = \frac{1}{C_1}\int_0^{(1-D)T_s} i_{L_1}\,dt. \tag{3}$$

The converter is optimized by considering dynamic and steady state responses of the system. Calculating the efficiency of the system can be carried out by comparing the input and output powers as seen in (4), where η is the efficiency, P_{out} is the output power and P_{in} is the input power

$$\%\eta = \frac{P_{out}}{P_{in}}\times 100 = \frac{(V_{out}\,x\,I_{out})}{(V_{in}\,x\,I_{in})}\times 100. \tag{4}$$

As a result of above mentions, the transfer function that describes the relationship between the input and output of a cuk converter can be written as in (5) [15]

$$G_{(s)} = \frac{V_g}{D'^2}\times$$
$$\times\frac{s^2\frac{L_1C_1}{D'} - s\frac{D^2L_1}{D^2R} + 1}{s^4\frac{L_1C_1L_2C_2}{D'^2} + s^3\frac{L_1C_1L_2}{D'^2R} + s^2\left(\frac{L_1C_1L_2}{D'^2} + L_2C_2 + \frac{D^2}{D'^2}L_1C_2\right) + s\left(\frac{L_2}{R} + \frac{D^2L_1}{D'^2R}\right) + 1}, \tag{5}$$

where, $D' = 1 - D$.

Once the converter is mathematically modelled, it is then simulated in MATLAB/Simulink to verify the mathematical model. Simulink model of the cuk converter is given in Fig. 2. A mosfet is used as switching device. Other parameters of the simulation circuit for the converter are presented in Table I.

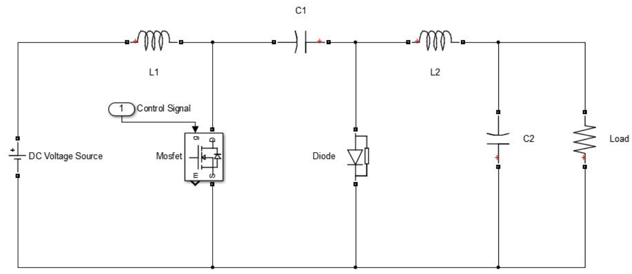


Fig. 2. Simulation diagram of the cuk converter.

TABLE I. PARAMETERS OF THE SYSTEM SIMULATED.

Parameter	Symbol	Nominal Value
Input voltage	V_{in}	100 V–800 V
Output voltage	V_{out}	311 V
Input capacitor	C_1	11 μF
Input inductor	L_1	0.5 mH
Output capacitor	C_2	1000 μF
Output inductor	L_2	0.5 mH
Switching frequency	f_s	10 kHz

III. PARALLEL CONNECTION MODEL

In order to design an optimum parallel connection model for hybrid energy sources, a basic hybrid system including a wind energy model and a solar system is selected as a case study. Cuk converters are connected to the output side of both sources to ensure the voltage stability and load sharing operations. A complete block diagram of the system can be seen on Fig. 3.

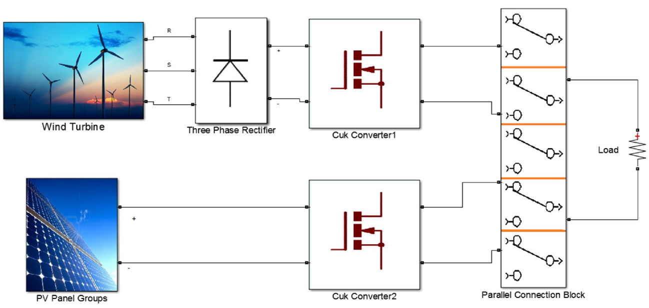


Fig. 3. Simulation model for the parallel connection operation.

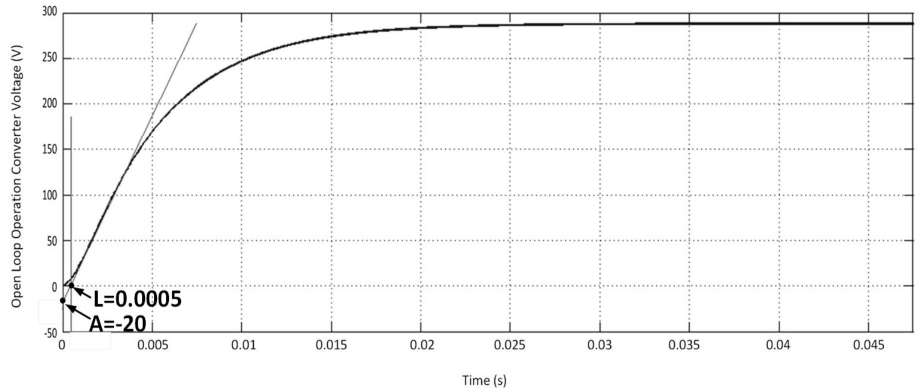


Fig. 4. Output voltage curve of open-loop operation.

Output voltage of each converter is fixed to a reference voltage by means of a PI controller. In the study, reference voltage value is selected as 311 V.

In PI controller, the proportional controller (Kp) has the effect of reducing the rise time and steady-state error, while the integral control (Ki) has the effect of eliminating the steady-state error. The parameters have been determined by using Ziegler Nicholas method to obtain the optimum performance from the system. For this aim, the system has been operated as open-loop firstly. The output voltage curve of open-loop operation is given in Fig. 4. This curve can be characterized by two constants, delay time L and time constant A, which are determined by drawing a tangent line at the inflection point of the curve and finding the intersections of the tangent line. Thus, required parameters (*A* and *L*) have been calculated by using this curve. Finally, the optimum PI parameters (K_P and K_i) have been found using (6) and (7) [16]:

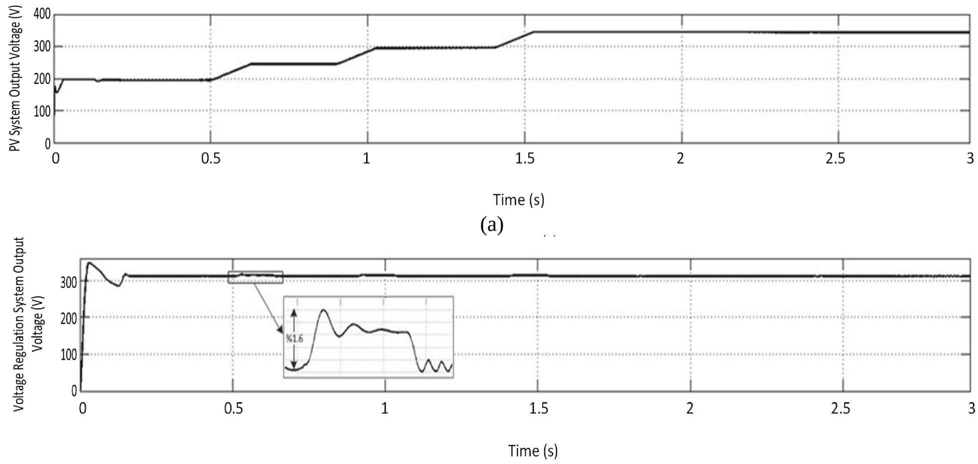
$$K_P = \frac{1.2}{A} = \frac{1.2}{20} = 0.06, \tag{6}$$

$$K_i = \frac{0.6}{AxL} = \frac{0.6}{20x0.0005} = 60. \tag{7}$$

In the simulation model developed, the PV panel is modelled as a controlled current source with variable input values. This is a common way of modelling PV systems [8]. To simulate the variations on the input side of energy source, similar characteristic variations are generated on the control input of current source. According to simulation results, it has been observed that the regulation system successfully fixes the output voltage to the reference voltage in a short time against the instant changes on the output voltage of the PV panel. Figure 5 illustrates the simulation results of the voltage regulating system for solar module. As seen on this figure, output voltage value of the regulation system has increased 1.6 % for a short time and after it was fixed to the reference value successfully.

As the second energy source of the hybrid system, a wind energy source has been selected. The wind energy module has been modelled by using a three phase asynchronous generator in Simulink environment. Fig. 6 demonstrates the output voltage signals of the generator and output voltage signal of the voltage regulation system as well. According to natural changes on wind power, output voltage and frequency of the 3-phase generator have been changed continuously as seen on Fig. 6. However, the voltage regulation system has fixed the output voltage to the reference voltage successfully, even the generator voltage increases or decreases.

Once the models for solar and wind energy systems have been designed separately, a parallel connection system has been designed to connect them in parallel on the same bus. For this aim, voltage equality between the output voltages of both systems are checked continuously by “Parallel Connection Block”, which is connected to the output side of each converter. A detailed schema of parallel connection control system is illustrated in Fig. 7.



(b)

Fig. 5. Simulation results of the voltage regulating system for solar module.

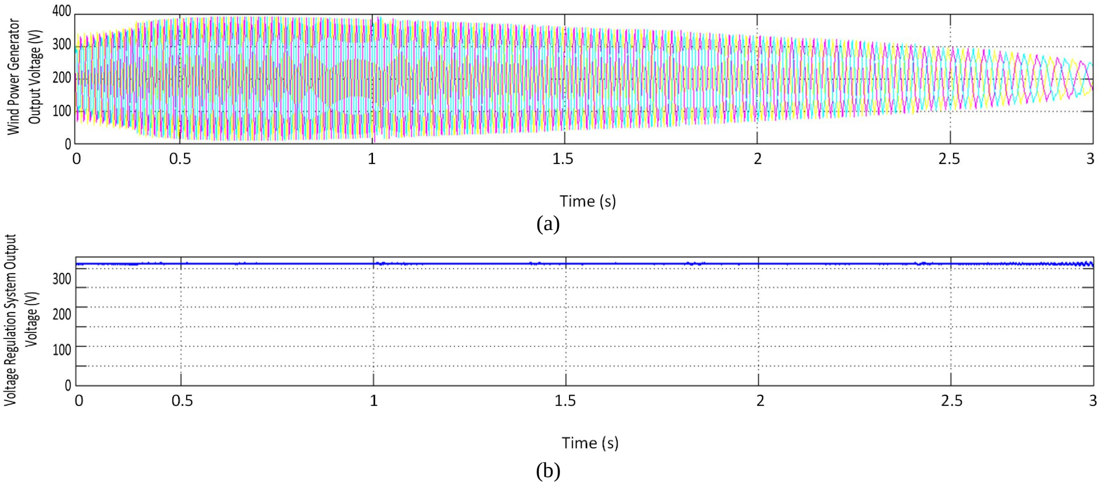


Fig. 6. Simulation results of the voltage regulating system for wind module.

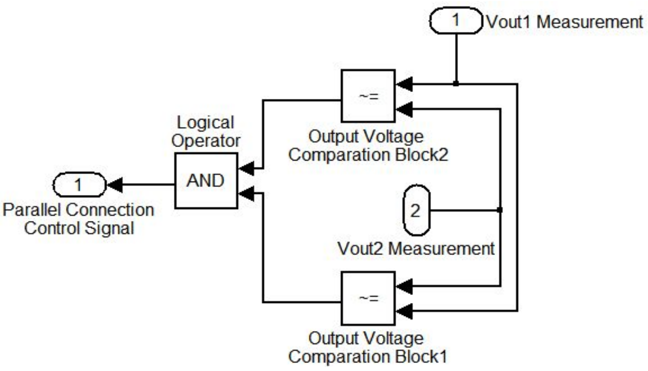


Fig. 7. Open-circuit schema of the safe parallel connection block.

If the system operates as open loop after the parallel connection operation is started, some undesired cases may appear like deactivating one of the converters, unbalanced loading and damaging the converters due to overloading. For this reason, a current control technique has been added to the system which also controls the load sharing between the sources. Thanks to this technique, currents drawn by the converters and total current drawn from the system by loads have been measured and controlled continuously by a second PI controller. Thus, a closed loop load sharing system has been obtained. A pre-defined load ratio has been used for the load sharing operation. For this, the total current drawn from the system is calculated firstly as just mentioned, and then optimum current flowing operation for each converter has been provided according to load ratio of each converter. Thus, the total load is shared by the converters successfully. Regarding to this principle, (8) is used for load sharing operation

$$I_1 = (I_1 + I_2) x \frac{load\ ratio}{100}. \quad (8)$$

Figure 8 illustrates the control block which provides the voltage stability and current control. The control signals required for the converters are generated by this block. Output voltage of the each converter is compared with the reference voltage value (311 V) continuously, and then an error signal is generated. The error signal is gone into the PI controller to generate the control signal. Also, another control signal for supplying the power demanded by loads is generated by totalizing the output voltages of both converters.

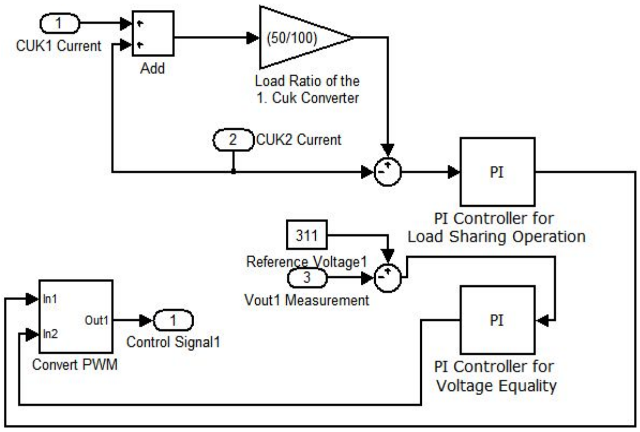


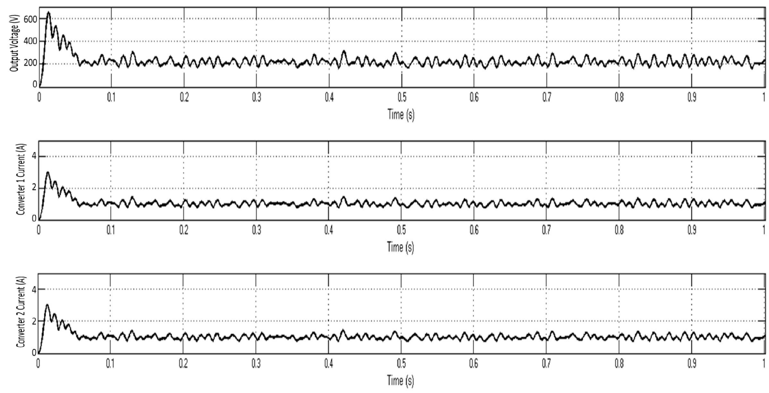
Fig. 8. Voltage regulation and current sharing control block.

IV. SIMULATION RESULTS

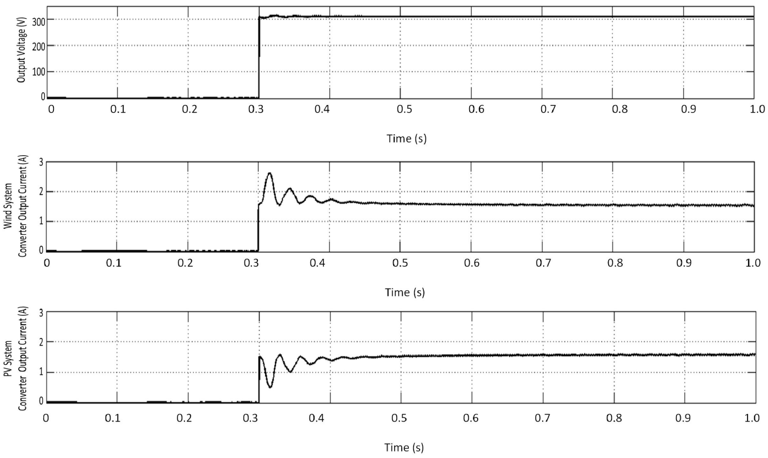
The system presented in this study is simulated under several conditions like different input voltages and different load sharing ratios. Some of the simulation results are given in this section.

As mentioned previously, the system is controlled by the PI control blocks. If the converters operate uncontrolled, some serious problems may occur like overshooting and instability. Figure 9(a) illustrates sample waveforms of voltage and current signals when the converters operate uncontrolled. On the other hand, if the system is operated with PI control, all these problems are eliminated. Figure 9(b) depicts the same waveforms when the system is controlled by the PI controller and the load is shared equally by the converters. As seen on Fig. 9(b), fixing the output voltage and current sharing operations are performed successfully. Also, parallel connection operation is achieved in a very short time, around 0.3 s, which means that the system has a fast response time.

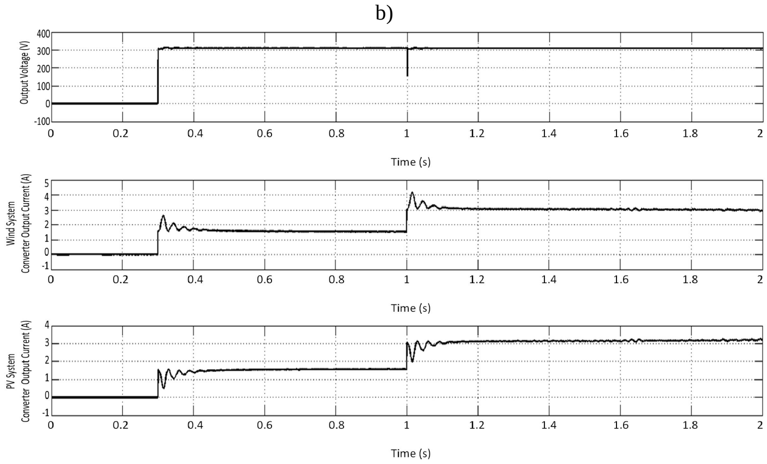
In the study, another test is carried out to observe the system response against the load variations after the system is passed to steady state conditions. The system response against the load variations is illustrated in Fig. 9(c) when the load is shared equally. As depicted on the figure, the load value is 100 ohm between 0 s and 1 s.



a)



b)



c)

Fig. 9. Waveforms of the output voltage and current values without PI control (a); Waveforms of the output voltage and current values with PI control (b); System response against the load variations (c).

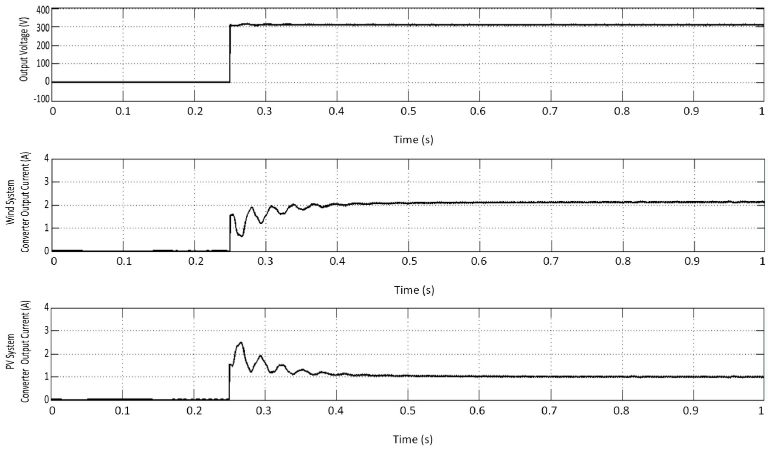


Fig. 10. System response under different load sharing ratios.

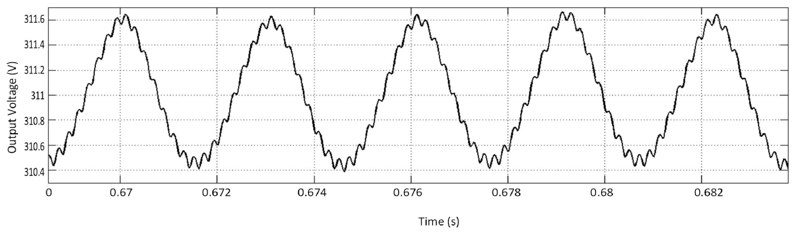


Fig. 11. The ripple on the output voltage of the system.

However, the load is decreased to 50 ohm after 1 s. As a result of this decrease, the output voltage is also decreased. However, the control system senses this variation on the voltage, and sets it to the reference voltage again. Hence, the negative effect caused by the load variation is eliminated in a very short time and load sharing operation is maintained successfully.

The presented load sharing system has been also tested for different sharing ratios. This situation can be observed in Fig. 10, where the wind system feeds the load with 70 % load ratio, and the PV system feeds it with 30 % load ratio. Figure 10 also illustrates that parallel operation of the system continues without any interruption, even input voltages of the converters have different values.

The ripple on the output voltage of the system is given in Fig. 11. It has been obviously seen that the ripple is quite less (1.2 V), around 0.385 %, which is highly considerable value [9]. Moreover, this ripple has been minimized by controlling the converters with high switching frequencies without using an external filter.

V. CONCLUSIONS

In this study, an effective parallel connection model for cuk converters has been developed to use it in multi-input energy systems. Firstly, the system is modelled and mathematically analysed. Once the converter is mathematically modelled, it is then simulated in MATLAB/Simulink in order to test the mathematical model and to define the required circuit parameters of the cuk converter. Then, a model for parallel connection operation is also developed and simulated in MATLAB/Simulink. According to simulation results, it has been observed that ripples on the output voltage of the converters are considerably minimized. Furthermore, parallel operation of the system has been maintained without any interruption, even though the energy sources have different input voltages. Transient state analysis of the system is also realized and it is observed that the system reaches to steady state conditions in a very short time.

In the system presented, load sharing operation among the converters is carried out by realizing the active current sharing techniques in order to ensure power flow control among the energy sources. The system presented is also tested against the instant load variations on the output side. Negative effects of the load variations are eliminated in a very short time and load sharing operation is maintained successfully under new load conditions.

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