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PI CONTROL OF A NOVEL POWER CONVERTER BY USING HEURISTIC OPTIMIZATION

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Abstract- In this study, obtaining the PI control coefficients of a power converter using the heuristic optimization method was investigated. A new converter has been designed to increase the lifetime of the energy storage unit of a satellite power subsystem. It is also possible to increase the active duty life of the satellite by using the aforementioned converter according to the increased battery life.

Keywords: Supercapacitor, Battery, Weinberg Converter, Buck Converter, Differential Evolution.

1. INTRODUCTION

The demand for energy storage units to provide uninterrupted energy to users is encouraging power electronics researchers [1]. Batteries are the most preferred unit for energy storage in satellites due to their high energy density. Supercapacitors have less energy density but higher power density than batteries, so they can be integrated with batteries for instantaneous power needs such as SAR load activation on satellites [2]. Satellites with payload types that draw high instantaneous currents have a shorter battery life. In a power subsystem architecture that uses a supercapacitor for instantaneous power requirements and batteries for average power requirements, this problem will be eliminated and the satellite mission life will increase according to the battery life [3].

For satellite applications, a Weinberg converter is used to increase the input voltage, and a Buck converter is used to reduce the input voltage. The battery voltage may be more or less than the supercapacitor voltage according to the satellite operating mode. Therefore, the proposed power converter between the battery and the supercapacitor should be capable of increasing and decreasing the input voltage. This is accomplished by the proposed converter, which combines the Weinberg and Buck converters in a single topology [4] and its topology is shown in Figure 1.

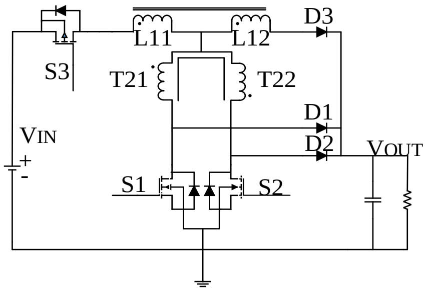

Figure 1. Block diagram of the mentioned power converter

Waveforms of the mentioned converter are analyzed for Buck and Weinberg mode operations. PI control is used for voltage mode control [5-7] and coefficients of PI control are obtained using differential evolution algorithm [8-11].

The operating modes of the power converter are described in section 2. In section 3, the differential evolution algorithm is presented, and the responses of the control coefficients obtained using the differential evolution algorithm of the mentioned power converter are analyzed in section 4. The characteristics of the research and future work are discussed in section 5.

2. OPERATION MODES OF MENTIONED POWER CONVERTER

The new power converter that combines Weinberg and Buck converters into a single topology is investigated in the scope of this study. The proposed converter can be operated without any instability problems by increasing and also decreasing the input voltage. As a difference from classical Weinberg converter, it is added a switch, named as S_3, between the input source and the inductor L_{11} in the proposed power converter. When the required supercapacitor voltage is greater than the battery voltage, switch S_3 is at ON state continuously and the converter operates as classical Weinberg converter, so the battery voltage increases to the target voltage. In this operation mode, when S_1 (or S_2) is at conduction, i_{T1} passes to ground by flowing through the coil T_1 (or T_2) of the transformer and S_1 (or S_2). The current which is at the same value will pass through T_2 coil ($i_{Q1} = i_{T2}$), because T_1 and T_2 have the same number of turns. Since S_2 (or S_1) is at cut off mode, i_{T2} passes through D_2 to the load. The transformer's middle point voltage (V_{CT}) is at the same value as the half of the load voltage as in Equation (1) [4]. This operation mode is shown in Figure 2.

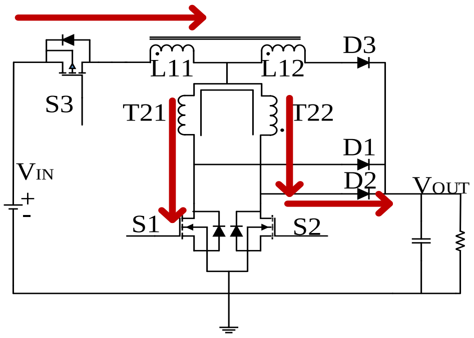

Figure 2. The current paths when S_1 is at ON state

$$[V_{CT}]_{ON} = \frac{V_{OUT}}{2} \tag{1}$$

When S_1 is at conduction mode, the input current i_{L1} is equal to the sum of the currents of S_1 and D_2 and this is also valid for the case when S_2 is at conduction mode. The output current is at the half value of input current i_{L1} as mentioned in Equation (4) [4].

$$i_{L1} = i_{S1} + i_{D2} \tag{2}$$

$$i_{S1} = i_{D2} = i_{OUT} \tag{3}$$

$$[i_{L1}]_{ON} = 2[i_{OUT}]_{ON} \tag{4}$$

$$V_{L1} = V_{IN} - \frac{V_{OUT}}{2} = L_1 \frac{\Delta i_{L1}}{\Delta t} \tag{5}$$

$$\left(\frac{\Delta i_{L1}}{\Delta t}\right)_{ON} = \frac{V_{IN} - \frac{V_{OUT}}{2}}{L_1 \left(\frac{\Delta i_{OUT}}{\Delta t}\right)_{ON}} \tag{6}$$

$$\left(\frac{\Delta i_{L1}}{\Delta t}\right)_{ON} = \frac{2V_{IN} - V_{OUT}}{4L_1} \tag{7}$$

The input current flows through D_3 when S_1 and S_2 are at cut off mode, thus input and output currents have the same value. The valid inductance value is equal to four times of the inductance of L_1 or L_2 due to the fact that they have the same turn number ($N = N_{L1} = N_{L2}$) [4]. This operation mode is shown in Figure 3.

$$L_{OFF} = (N_{L1} + N_{L2})^2 A_L = 4N^2 A_L = 4L_1 \tag{8}$$

$$[i_{L1}]_{OFF}\, 2N = [i_{L1}]_{ON}\, N \tag{9}$$

$$[i_{OUT}]_{OFF} = i_{D3} = [i_{L1}]_{OFF} = \frac{1}{2}[i_{L1}]_{ON} \left(\frac{\Delta i_{L1}}{\Delta t}\right)_{OFF} \tag{10}$$

$$= \left(\frac{\Delta i_{OUT}}{\Delta t}\right)_{OFF} = \frac{V_{IN} - V_{OUT}}{4L_1} \tag{11}$$

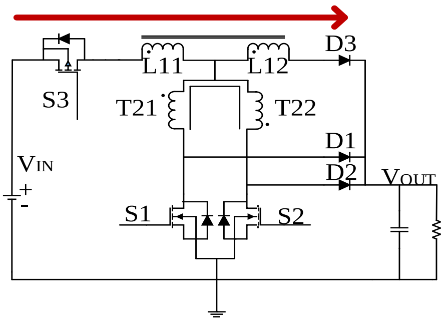

Figure 3. The state when S_1 and S_2 are OFF that mentioned power converter operates on Weinberg mode

Equations (12) and (13) can be interpreted according to the derived equations [4].

$$V_{IN} - V_{CT} = V_{CT} - V_{OUT} \tag{12}$$

$$[V_{CT}]_{OFF} = \frac{V_{IN} + V_{OUT}}{2} \tag{13}$$

At steady state operation the increase and decrease in current are equal according to Equation (14) [4].

$$\left[\frac{2V_{IN} - V_{OUT}}{4L_1 D_1}\right] + \left[\frac{(1-D_1)(V_{IN} - V_{OUT})}{4L_1}\right] = 0 \tag{14}$$

Equation (15) can be derived from Equation (14) [4].

$$V_{OUT} = (1 + D_1)V_{IN} \tag{15}$$

When the required supercapacitor voltage is smaller than the battery voltage, then the mentioned converter will be operated on buck mode. In this operation mode, S_1 and S_2 should be at cut off mode constantly and freewheeling current of the circuit when S_3 is at cut off mode circulate through the body diodes of S_1, S_2 and L_{12}. This operation mode is shown in Figure 4.

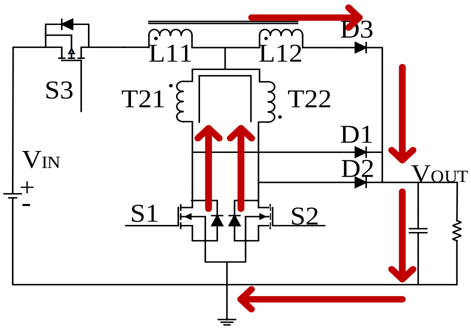

Figure 4. The Buck mode operation when S_3 is at off state

When S_3 is at conduction mode, the current will pass through L_{11}, T_{21}, T_{22}, D_1 and D_2. This operation mode is shown in Figure 5.

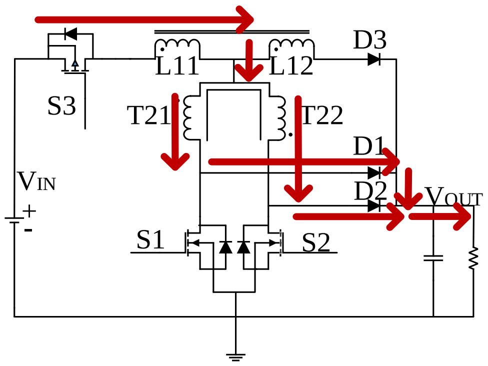

Figure 5. The Buck mode operation when S_3 is at on state

There will be no saturation problem in the transformer because of turning the windings of T_{21} and T_{22} around the same core. The novel power converter will be operated as classical Buck converter for that operation mode. Considering the voltage on the input inductor as V_L, the source voltage as V_{IN}, the load voltage as V_{OUT}, the voltage on the transformer coils as V_T, the duty cycle of S_3 as D_2 and the period as T, the following equations are derived.

$-V_{IN}+V_L+V_T+V_{OUT}=0$ (KVL equation with the left-half of the transformer) (16)

$-V_{IN}+V_L-V_T+V_{OUT}=0$ (KVL equation with the right-half of the transformer) (17)

$$V_L=V_{IN}-V_{OUT} \quad (18)$$

When S_3 is at cut off mode, Equation (19) can be written [4].

$$V_L=-V_{OUT} \quad (19)$$

Equation (20) and Equation (21) are derived for steady state condition [4].

$$(V_{IN}-V_{OUT})D_2T+(-V_{OUT})(T-D_2T)=0 \quad (20)$$

$$V_{OUT}=D_2V_{IN} \quad (21)$$

It can be interpreted that the voltage at the output of the converter is $(1+D_1)V_{IN}$ when the required supercapacitor voltage is greater than the battery voltage and is D_2V_{IN} when the required supercapacitor voltage is smaller than the battery voltage.

The novel power converter can be used for increasing and also decreasing the input voltage by these operation modes. Parasitic effects are ignored here to derive steady-state equations [4].

3. DIFFERENTIAL EVOLUTION ALGORITHM

Differential evolution is a heuristic algorithm presented by Rainer Storn and Kenneth Price in 1995. The basis of this algorithm is evolution. Differential evolution looks alike genetic algorithm according to working principles. The coding of the algorithm is simple and the algorithm can ensure solutions with high performance in a short time. The pseudocode of DE is given below [8-11].

```
Population creation-randomly
Initial population calculation
DO
        FOR every chromosome in population
        Mutant vector obtaining
        Trial vector obtaining by using crossover value
        Trial vector calculation
        IF calculation of trial vector is worse than
calculation of initial vector
        Assigning initial vector values to target vector
values
        ELSE Assigning trial vector values to target
vector values
        END
   WHILE maximum iteration or minimum error state is
not obtained
END
```

The values of population dimension, population size, iteration number, limits, crossover ratio (*CR*), and scaling factor (*F*), that can be had by chromosomes are presented at the beginning of the differential evolution code. Crossover ratio and *F* are between [0,1] values. For the novel power converter that controlled by using PI control, $Voltage\_Kp$, and $Voltage\_Ki$ values should be calculated, so the dimension of population is 2. By doing some trials, it is determined that the best results are observed by presenting population size as 20, iteration number as 25, maximum limit of $Voltage\_Kp$ as 1, maximum limit of $Voltage\_Ki$ as 1000 for Weinberg operation, maximum limit of $Voltage\_Kp$ as 100, maximum limit of $Voltage\_Ki$ as 100000 for Buck operation, minimum limits of chromosomes as 0, CR as 0.9, and *F* as 0.1. Initial vectors can be created by random method at the beginning of the code. The calculation of the initial vectors is realized after the creation of population.

Three vectors are selected in mutation stage by random method. The difference of two vectors is calculated, this value is multiplied by *F*, and added to third vector. The formed vector called mutant is obtained by using that procedure. Trial vector is created by using initial vector and mutant vector in crossover stage. If vector values exceed the borders of the limits after calculations, limit values assign to these values. A random number between [0, 1] values is taken and compared with *CR* value. If random number is smaller than or equal to *CR* value, trial vector value is produced by using mutant vector. Otherwise, it is produced by using initial vector. Trial vector values are examined. If they ensure high performance than initial vector, they are assigned to target vector.

The algorithm is concluded when maximum iteration number or minimum error criterion is reached. Otherwise, the mutation step is reiterated [8-11]. The algorithm is run twice because of having two operation modes as Weinberg mode and Buck mode of the novel converter, so the control coefficients are obtained for two different operation modes separately.

Cost function is formed simply on the basis of minimizing the error value between output voltage and reference value. The results are investigated during iterations and the best results are obtained by using MATLAB software.

4. PI CONTROL RESULTS

The results of simulations that performed by using PSim software are presented in this section. The parameters used for simulations are presented in Table 1.

Table 1. Hardware parameters of the prototype

Parameter	Value
V_{IN}	80-120 V
V_{OUT}	100±5 V
P_{OUT}	500 W
Transformer	L_{T21}= L_{T22}= 200 μH
Inductor	L_{L11}= L_{L12}= 2 mH
Output Capacitor	200 μF

Voltage mode control is used because of any requirements for current sharing between different modules and PI control is preferred because of providing zero steady-state error under line and load changes [5-7]. PI control coefficients obtained by using differential evolution algorithm for different operation modes of the novel power converter are presented in Table 2.

Table 2. Obtained control coefficients by using differential evolution algorithm

Coefficient	Value
K_p (Buck mode-proportional coefficient)	35
K_i (Buck mode-integral coefficient)	33334
K_p (Weinberg mode-proportional coefficient)	0.12
K_i (Weinberg mode-integral coefficient)	100

The responses of the mentioned converter are analyzed. The analyzes are performed by using the limit values of the input voltage for both operation modes. $V_{DS}\_WEINBERG1$ and $I\_WEINBERG1$ belongs to S_1, $V_{DS}\_WEINBERG2$ and $I\_WEINBERG2$ belongs to S_2, and V_{DS}_BUCK1 and I_BUCKG1 belongs to S_3, respectively.

The graphics for Weinberg mode as input and steady-state output voltages are shown in Figure 6, drain-source voltages of the switches in Figure 7 and currents of switches in Figure 8, respectively. It can be interpreted from the figures that S_3 is always on conduction mode and S_1 and S_2 switch with 180° phase difference for Weinberg operation mode.

It is shown the graphics for Buck mode as input and steady-state output voltages in Figure 9, drain-source voltages of the switches in Figure 10 and currents of switches in Figure 11, respectively. It can be interpreted from the figures that S_3 switches according to error signal and S_1 and S_2 are always on cut off mode and current circulates from the body diodes for Buck operation mode.

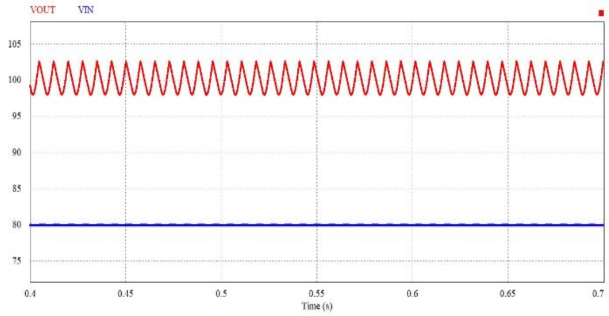

Figure 6. Input and output voltages for V_{IN} = 80 V (Weinberg mode)

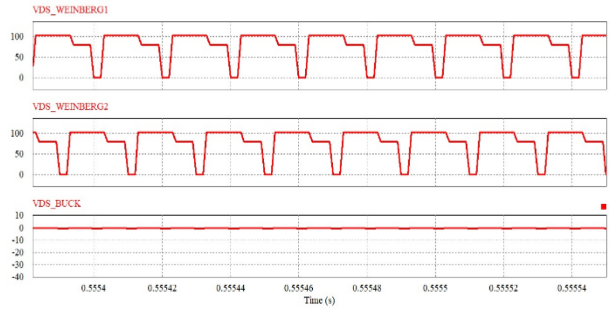

Figure 7. Drain-source voltages of the switches for V_{IN} = 80 V (Weinberg mode)

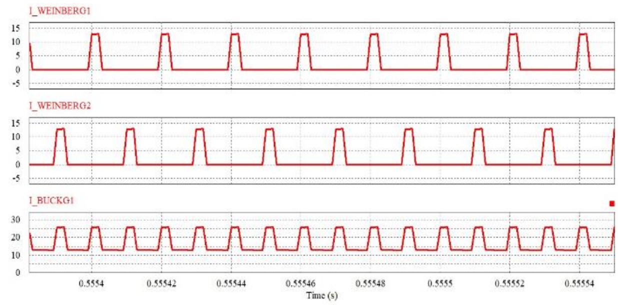

Figure 8. Currents of switches for V_{IN} = 80 V (Weinberg mode)

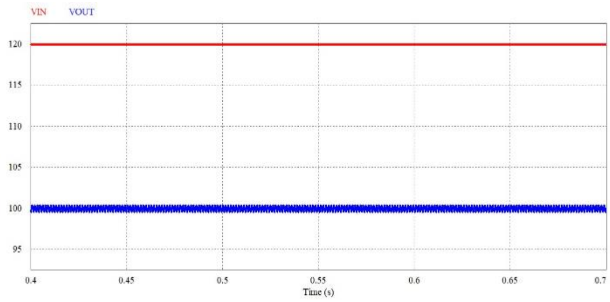

Figure 9. Input and output voltages for V_{IN} = 120 V (Buck mode)

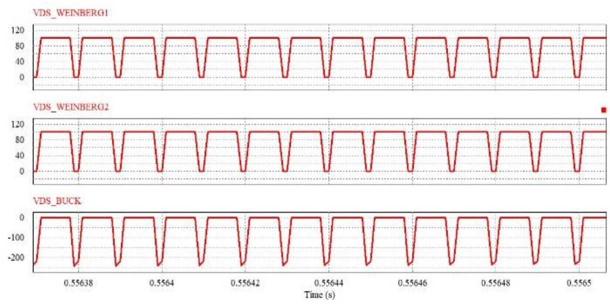

Figure 10. Drain-source voltages of switches for V_{IN} = 120 V (Buck mode)

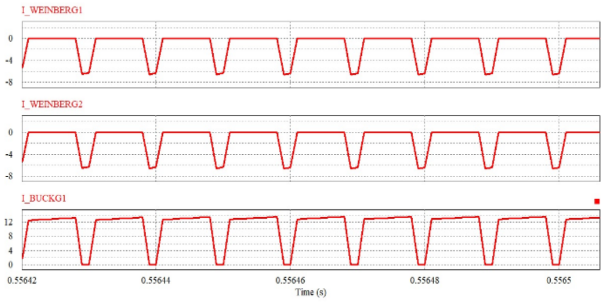

Figure 11. Currents of switches for V_{IN} = 120 V (Buck mode)

It can be seen in the simulations that load voltage is reached the reference value for Weinberg mode and Buck mode S_3 is at conduction mode constantly and S_1 and S_2 are switching with 180° phase shift with each other for Weinberg mode operation, and S_1 and S_2 are at cut off mode and S_3 is switching for Buck mode operation as expected with theoretical equations. Control results that obtained by using differential evolution algorithm provide high performance.

5. CONCLUSIONS

The proposed power converter is controlled by PI control and control coefficients are obtained by using differential evolution algorithm in the scope of this study. The converter is designed to feed the supercapacitor from battery to extend the lifespan of battery and compensate SAR satellites' instantaneous power demands. The battery life, consequently the satellite life, will be increased by ensuring the instantaneous power demands by using supercapacitor instead of the battery. The mentioned converter will be located between the battery and the supercapacitor and has the ability to control the supercapacitor voltage in the values between $D_2 V_{IN}$ and $(1+D_1)V_{IN}$. Theoretical equations are supported by simulation results. Control coefficients obtained by using differential evolution algorithm are obtained in short time and results of simulations are pretty good. Output voltage is settled at reference value. It can be applied by changing circuit and control parameters for different design requirements easily. It is planned to add different parameters like phase margin, maximum overshoot value into cost function, design a control structure with two loops as in current control scheme, and try other intelligent optimization methods to obtain control coefficients for future works, thus it is intended to compare performances for different conditions.

NOMENCLATURES

1. Acronyms

CR	Crossover Ratio
DE	Differential Evolution
F	Scaling Factor
KVL	Kirchhoff's Voltage Law
PI	Proportional Integral
SAR	Synthetic Aperture Radar

2. Symbols / Parameters

D_1 : Duty cycle for Weinberg operation mode

D_2 : Duty cycle for Buck operation mode

I_BUCKG1 : Current of S_3

$I\_WEINBERG1$: Current of S_1

$I\_WEINBERG2$: Current of S_2

Kp : Proportional coefficient for PI control

Ki : Integral coefficient for PI control

P_{OUT} : *Output power*

V_{DS}_BUCK1 : Drain-source voltage of S_3

$V_{DS}\_WEINBERG1$: Drain-source voltage of S_1

$V_{DS}\_WEINBERG2$: Drain-source voltage of S_2

V_{IN} : *Input voltage*

$Voltage\_Kp$: Proportional coefficient for PI control

$Voltage\_Ki$: Integral coefficient for PI control

V_{OUT} : Output voltage

REFERENCES

[1] E. Demirkutlu, I. Iskender, "Three-Phase Buck Type PFC Rectifier for Electrical Vehicle Battery Charger", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 41, Vol. 11, No. 4, pp. 51-56, December 2019.

[2] A. Maddu, A. Saputra, N.I. Ayuningtiyas, A. Tsalsabila, A. Ismayana, N. Nurhalim, S. Arjo, "Synthesis of MnO_2/Carbon Dots Nanocomposite Derived from Rice Husk for Supercapacitor Electrodes", International Journal of Renewable Energy Research, Vol. 8, No. 3, pp. 1476-1482, September 2018.

[3] J.A.D. Hosseini, M. Moazzami, H. Shahinzadeh, "Optimal sizing of an isolated hybrid wind/PV/battery system with considering loss of power supply probability", Majlesi Journal of Electrical Engineering, Vol. 11, No. 3, September 2017.

[4] G. Tulay, M. Karakaya, I. Iskender, "Control of a Novel Power Converter of a Satellite Power Subsystem by Differential Evolution Algorithm", The 17th International Conference on Technical and Physical Problems of Engineering (ICTPE), pp. 24-28, 18-19 October 2021.

[5] G. Tulay, I. Iskender, A. Mamizadeh, "Boost PFC PI Control by Using Heuristic Optimization Method", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 18, Vol. 6, No. 1, pp. 167-171, March 2014.

[6] A. Karaarslan, "Modeling and Performance Analysis of Cuk Converter Using PI and OCC Method", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 36, Vol. 10, No. 3, pp. 1-5, September 2018.

[7] A. Karaarslan, "The Implementation of One Cycle Control Method to Inverting Buck-Boost Converter", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 35, Vol. 10, No. 2, pp. 14-19, June 2018.

[8] G. Tulay, I. Iskender, H. Erdem, "Optimal Tuning of a Boost PFC Converter PI Controller Using Heuristic Optimization Methods", International Transactions on Electrical Energy Systems, Issue 12, Vol. 27, pp. 1-10, October 2017.
[9] A. Kumar, B.K. Jha, S. Das, R. Mallipeddi, "Power Flow Analysis of Islanded Microgrids: A Differential Evolution Approach", IEEE Access, Vol. 9, pp. 61721-61738, April 2021.
[10] X.F. Liu, Z.H. Zhan, J. Zhang, "Resource-Aware Distributed Differential Evolution for Training Expensive Neural-Network-Based Controller in Power Electronic Circuit", IEEE Transactions on Neural Networks and Learning Systems, pp. 1-11, May 2021.
[11] S.M. Parida, P.K. Rout, "Differential Evolution with Dual-Mode Mutation for Parameter Estimation of Different Photovoltaic Models", The 1st Odisha International Conference on Electrical Power Engineering, Communication and Computing Technology (ODICON), pp. 1-6, May 2021.

BIOGRAPHIES

Gencer Tulay received his B.Sc. degree in Electrical and Electronics Engineering from Baskent University, Ankara, Turkey as a scholarship student in 2009, the M.Sc. degree in Electrical and Electronics Engineering from Gazi University, Ankara, Turkey in 2013 and Ph.D. in Electrical and Electronics Engineering in Gazi University, Ankara, Turkey in 2021. His research interests are power electronics, analog circuit design and heuristic optimization methods.

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