Employing Thermoelectric Coupled Solar PV Hybrid System in Non-conventional Distribution Generation

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Abstract The inflation of clean, efficient, sustainable, effective, secure, and reliable electricity demand has been triggered much interest for distribution generation at a miraculous and quickened pace. The necessity of reliability enhancement, diversity of fuel, cutback of greenhouse gases, severe weather fluctuation, etc. has stimulated the inclusion of Microgrid concept not only in utility level but also in customer and community level. Incorporation of solar photovoltaic (SPV) and thermoelectric (TE), termed as Solar photovoltaic-thermoelectric (SPV-TE) hybrid system is found to be a very promising technique to broadening the utilization of solar spectrum and enhancing the power output effectively-cum-efficiently. This hybrid architecture caters electrical energy with additional thermal energy that signifies upon harnessing of solar insolation in an exceptional way. This paper portrays on implementation of the aforementioned SPV-TEG coupled system in Non-conventional Distribution Generation in order to retrieve enough power from SPV array giving rise to higher active power delivery to the system and lower the reactive power absorbance by the system. The comparative analysis is done under subsystem such as SPV-TEG-Wind

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Energy system (WES) over SPV-WES on the basis of active and reactive power. The system is modeled, analyzed and validated under MATLAB-Simulink environment.

Keywords Solar PV system · TEG · Non-conventional distribution generation · Wind energy system · Reactive power · Active power

1 Introduction

Supplementary energy resources are becoming mandatory upon the enduring energy reserves to cope with the energy demand of surging population and technological advancement in the world [1]. Though the Sun is a boundless energy resource which also clean as well as unreservedly available energy resource from nature, it suffers from the curse of having lower efficiency upon the most used renewable energy resources. Concentrated solar photovoltaic modules (CPV) are also sunlight based energy generator that converts a portion of solar irradiance into electrical energy having much more efficient than traditional solar PV system. Several portions of the solar irradiation have wasted as heat while converting sunlight into electricity. SPV system suffers from having lower quantum efficiency as it dissipates greatly (around more than half) of the solar irradiation as heat. Hence by utilizing the dissipated heat into the conversion of electricity the power generation and ultimately efficiency can be increased. Many researchers have been working on the hybridization of solar PV-Wind energy system (WES)-FCT, its control aspect, storage. In the source side design of MPPTs for SPV and WES such as optimization-based MPPT, Modified MPPT raises the system cost as well as mathematical complexity [2]. As per our knowledge, implementation of SPV-TEG based system has not been employed in non-conventional distribution generation yet. Most of the researchers have been working upon the hybridization of solar PV, WES and FCT based power generating sources in Microgrid resulting substantial generation of active power and reactive power [3–5]. These papers lag the complete use of solar irradiation for extracting a significant amount of power from the solar PV array resulting in higher electrical efficiency. But as far as our concern, implementation of solar PV-TEG based hybrid system in conventional Microgrid has not been studied yet. The novelty of the paper lies in the employment of aforementioned technique (SPV-TEG hybrid system) for availing higher active power and lesser reactive power from the traditional Microgrid. Finally, system performance has been studied in this paper for employment of SPV-TEG based system in non-conventional distribution generation system under zero fault and numerous faulty conditions.

2 System Modeling and Description

The modeling of thermoelectric generator (TEG) and solar PV modules (SPV) have been performed by insertion of corresponding number of modules in parallel and series as per the requirement. After being designed individually, both the systems have been combined in order to perform the study upon the hybrid system. The model is described in individual subsection namely:

- Modeling of Solar PV array
- Modeling of TEG
- Modeling of WES
- Modeling of DC–DC Converter
- Modeling of VSC (Voltage Source Converter)
- Modeling of Control Algorithm
- Modeling of Filter
- Modeling of Electrolyzer and its bidirectional converter.

2.1 *Modeling of Solar PV Array*

Solar irradiation and temperature on the solar PV module surface are solely responsible for the characteristics of SPV array. As the solar irradiance upon the SPV array is increased, the power generated from SPV array is also increased. In order to construct an SPV array, number of SPV modules need to combine in a particular fashion either in series or parallel to obtain the requisite power. The equivalent circuit of the solar cell is shown in Fig. 1 where I_{ph} defines the function as current source, R_{sh} defines the internal shunt resistance, R_{se} is the series resistance and a diode connected in parallel with the current source [6]. The output current of the solar PV module

$$\text{i.e. } I_{pv} = N_p I_{ph} - N_p I_0 \left[\exp\left\{ \frac{q\left(V_{pv} + I_{pv} R_s\right)}{N_S AkT} \right\} - 1 \right] - I_{sh} \tag{1}$$

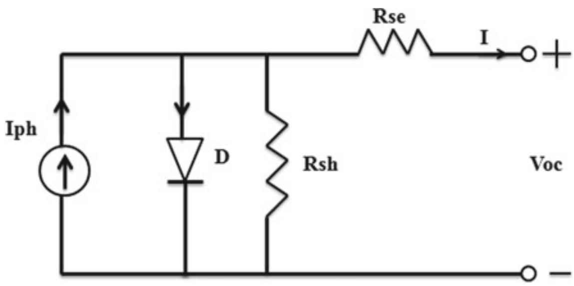

Fig. 1 Equivalent circuit of solar cell

Table 1 Specification of TEG module

Parameters	Values
Open circuit voltage (V)	8.8
Cold junction temperature (°C)	30
Hot junction temperature (°C)	300
Load resistance (Ω)	1.25
Load output voltage (V)	4.27
Load output power (W)	15
Load output current (A)	3.52
Heat flow density (W/cm^2)	~12
Heat flow across the module (W)	~370

where k = Boltzmann's constant = 1.3805×10^{-5} J/K, A = ideality factor of the solar PV cell depend on PV manufacturing technology, some of them are presented in Table 1, T = operating temperature of the module, $q = 1.6 \times 10^{-19}$ C.

2.2 *Modeling of Thermoelectric Generator*

The working of TEG constitutes of three elementary thermoelectric effects with two accessorial effects. The three elementary effects are named as Seebeck effect, Peltier effect, and Thomson effect while the accessorial effect can be named as Joule effect and Fourier effect. Seebeck effect is responsible for electromotive force (EMF) and Peltier heat, Thomson heat and Joule heat are caused by the effect of Peltier, Thomson, and Joule, respectively. As a matter of fact, Peltier effect is not an interface effect; it produces heat only at the end sides of the semiconductors. Volumetric effects like Thomson and Joule heat production are pretended to be uniformly transferred to the cold and hot junctions of the semiconductor elements [7]. Though the Thomson effect is very small it is often neglected in many cases.

For steady-state analysis at cold and hot junction of TEG an energy balance equation is used which can express as follows (2) and (3):
Mathematically

$$Q_h = \propto * T_h * I - k_{\text{tc}} \Delta T - 0.5 I^2 R \tag{2}$$

$$Q_c = \propto * T_c * I - k_{\text{tc}} \Delta T + 0.5 I^2 R \tag{3}$$

The electrical current can be expressed as (4):

$$I = \frac{\propto \Delta T}{(1+n)R} \tag{4}$$

Table 2 Modeling parameters at steady state

Parameters	Symbols	Corresponding values
Seebeck coefficient	$\propto$	0.035 V/K
Resistance	Ω	1.22
Thermal conductivity	k_{tc}	20.91 W/K
Figure of merit	Z	$0.387 \times 10^{-6}K^{-1}$

The short circuit current is the maximum current at a load voltage of zero i.e. $V_L = 0$. Hence can be written as (5):

$$I_{SC} = 2I_m = \frac{2W_m}{V_m} \tag{5}$$

Finally, the voltage of TEG can be expressed by using Ohm's Law, and the corresponding equation obtaining short circuit current and current through TEG is shown in Eq. (5)

$$V = -R(I - I_{SC}) \tag{6}$$

A model of TEM specified by TEPI-12656-0.6 has been used over here to model the hybrid system and the behavioral analysis has been conducted. The parameter specifications of the thermoelectric module (TEM) have been listed in Table 1. The constraints that have been considered for modeling are presented in Table 2.

2.3 *Modeling of Wind Turbine*

About 350–400 W power is generated from a permanent magnet based self-regulated variable speed wind turbine at a wind speed of 12 m/s. Stall control or self-control can be achieved by adjustment of wind turbine blades in a particular direction. At a wind speed of 17 m/s this wind turbine can be able to extract power from the wind.

The aerodynamics of the rotor can be stated as (7)

$$P_w = \frac{C_p \rho A v_w^3}{2} \tag{7}$$

where P_w = wind power,
C_p = Power coefficient.

2.4 Modeling of Electrolyzer

A resistor (contact resistance) connected in series with the controlled voltage source (CVS) is considered for modeling of an Electrolyzer. A shepherd's model has been used for representation of nonlinear voltage which varies with amplitude of current and amplitude of the actual voltage. The CVS can be represented mathematically as (8):

$$E = E_0 - K\frac{Q}{Q - \int i\,\mathrm{d}t} + A\exp(-B\int i\,\mathrm{d}t) \tag{8}$$

where E is No Load Voltage, E_0 is Constant Electrolyzer Voltage, K is the Polarization Voltage, Q is the Capacity of Electrolyzer, A is the Exponential Voltage, B is the Exponential Capacity, i is the Current of the Electrolyzer. Bidirectional converter is an integral part of connecting an Electrolyzer with a system. As the name suggests the flow of power is in both the directions. Generally, system integrated with Fuel Cell, Supercapacitors use bidirectional converter for power flow in both directions.

2.5 Modeling of DC–DC Converter

In order to step up the voltage at the output of the terminal, dc–dc converter is used which is also termed as boost converter.

It can be stated as (9)

$$V_0 = \frac{V_s}{1 - D} \tag{9}$$

where

V_0 denotes Output Voltage of the System
V_s denotes Input/Source Voltage of the System
D denotes Duty Cycle (it varies from 0 to 1).

2.6 Modeling of Voltage Source Converter (VSC)

For mitigation of power quality issues, converting dc side voltage into ac voltage for feeding it to the grid; VSC is connected to the system. This can also act as an active shunt filter. Natural a-b-c reference frame has been considered for modeling of the VSC. The following equations have been used in order to model the VSC.
Mathematically,

$$S_a = 2S_1 - 1 \tag{10}$$

$$S_b = 2S_3 - 1 \tag{11}$$

$$S_c = 2S_5 - 1 \tag{12}$$

$$V_{\text{ia}} = \left(\frac{2}{3}\right) * \frac{V_{\text{dc}}}{2} * S_a - \frac{1}{3}S_b - \frac{1}{3}S_c \tag{13}$$

$$V_{\text{ib}} = \left(\frac{2}{3}\right) * \frac{V_{\text{dc}}}{2} * S_b - \frac{1}{3}S_a - \frac{1}{3}S_c \tag{14}$$

$$V_{\text{ic}} = \left(\frac{2}{3}\right) * \frac{V_{\text{dc}}}{2} * S_c - \frac{1}{3}S_a - \frac{1}{3}S_b \tag{15}$$

where,

S_a, S_b, S_c	define three-phase Switches (Eqs. 10–12);
S_1, S_3, S_5	define Switching state of switches;
$V_{\text{ia}}, V_{\text{ib}}, V_{\text{ic}}$	define Voltage output of inverter (Eqs. 13–15);
V_{dc}	define DC link voltage.

2.7 Modeling of Control Strategy of VSC

There is a self-uniqueness of this control strategy for operation during healthy as well as faulty conditions. The control strategy thus used is found to be efficient as after the clearance of fault, it brings the system back to the steady-state. No controller will be going to work during fault; hence the control strategy is designed in such a way that as soon as the fault is cleared the system comes back to the initial position as soon as possible. Whatever non-conventional sources are proposed to integrate this strategy holds well every time. A multiplication factor of 0.0045 is considered for phase voltages. The control strategy thus used can be shown in the block diagram in Fig. 2.

2.8 Filter Modeling

Though the system uses many power electronics-based switches there is the chance of generation of harmonics in the system. In order to lessen the harmonics filter circuits have been implemented. The Synchronous reference frame (SRF) has been used in order to model the filter circuit that can be explained below.

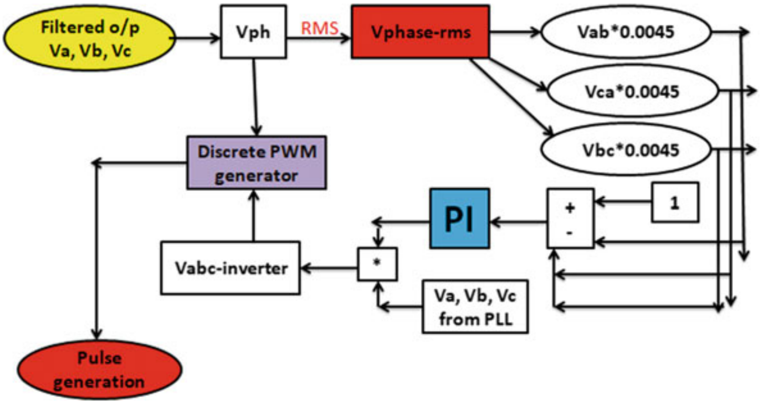

Fig. 2 Control strategy of VSC generating gate signal

$$V_{\text{id}} = R_f i_{\text{d}} + L_f \frac{\text{d}i_{\text{d}}}{\text{d}t} - \omega_e L_f i_{\text{q}} \tag{15}$$

$$V_{\text{iq}} = R_f i_{\text{q}} + L_f \frac{\text{d}i_{\text{q}}}{\text{d}t} + \omega_e L_f i_{\text{d}} \tag{16}$$

where,

R_f denotes Resistance of Filter;
L_f denotes Inductance of Filter;
ω_e Denotes Angular Frequency;
i_{d}, i_{q} denotes d and q-axis inverter currents;
V_{id}, V_{iq} denotes d and q-axis inverter voltages.

3 Proposed System Configuration

Figure 3 shows the pictorial presentation of the proposed system.

The figure represents the proposed system of employing thermoelectric generator (TEG) in NDG. The newness of this work lies in integrating TEGs with solar PV array so that the power generation from the RE sources could be maximized in a significant manner. As per our knowledge, implementation of TEGs has not yet considered for Microgrid. Hence the proposed system is compared with conventional NDG to infer the superiority of employing TEGs to NDG.

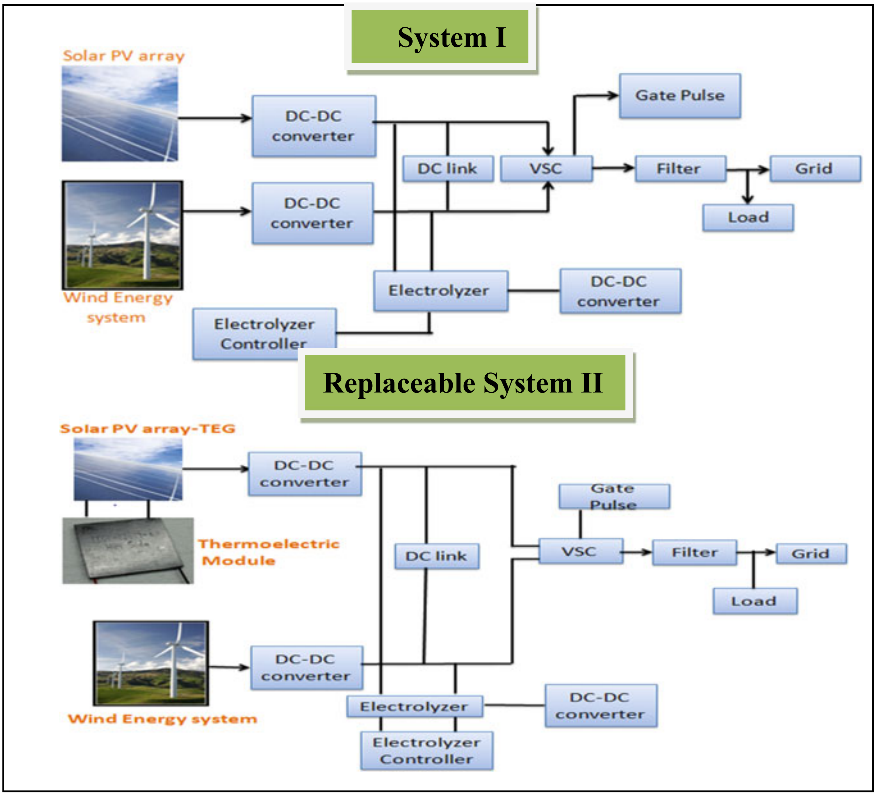

Fig. 3 System I to be compared with proposed system configuration

4 Results and Discussion

The system is subjected to healthy condition as well as several variations (fault conditions). The reliability of the whole NDG system is studied for several parameters such as active power delivered to the system by the RE sources (P) and Reactive power supplied to the system (Q). The control strategy applied to the system has been studied precisely during variations. Because the main aim of control strategy will be defined best when the fault is cleared means as soon as the fault is cleared the control strategy starts its action in order to retain the system back to the initial condition. Thus the applicability of the proposed system is verified for healthy condition (during zero fault), and faulty conditions such as Line-to-Ground (L-G) fault.

4.1 During Healthy Condition (Zero Fault Condition)

The proposed system is integrated with TEG in order to utilize the significantly lost heat by solar PV modules which are integrated into conventional Microgrid integrated with WES.

Solar PV array receives solar insolation for the generation of electricity. In Fig. 4, the active power thus generated by the proposed system is about 1.86 times to the conventional NDG. Similarly in Fig. 5, the reactive power generation is found to quite lesser i.e. equivalent to 2.93 times than the system I.

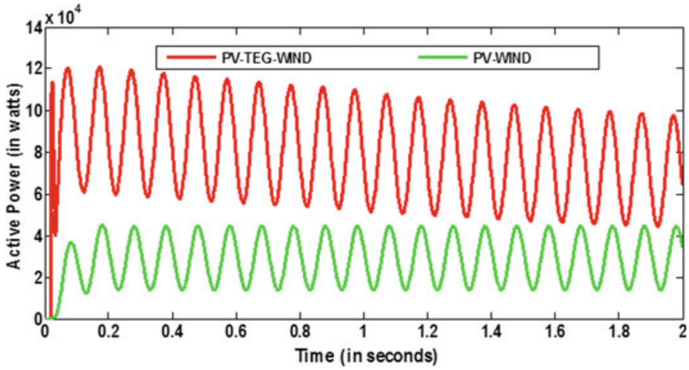

Fig. 4 Active power delivered for PV-TEG-WIND and PV-WIND system

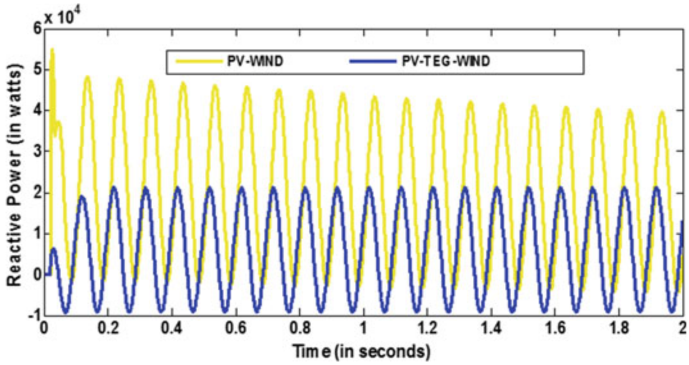

Fig. 5 Reactive power delivered for PV-TEG-WIND and PV-WIND system

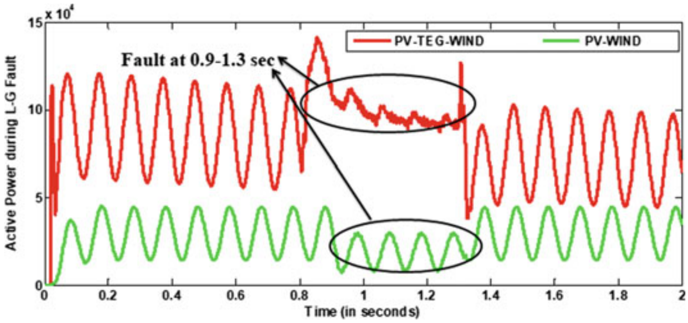

Fig. 6 Active power during L-G fault for PV-TEG-WIND and PV-WIND system

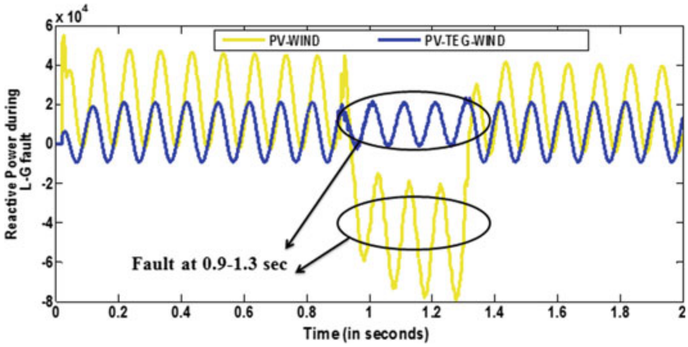

Fig. 7 Reactive power during L-G fault for PV-TEG-WIND and PV-WIND system

4.2 During Line to Ground Fault Condition

The proposed system is studied under fault conditions in order to check the reliability of the controller during disturbances. The system fault is created in virtual scenario. In the above studied single L-G fault active power, reactive power, solar power is shown in Figs. 6 and 7. It can be inferred that the controller acts precisely as the overall system comes back to steady-state just after the fault is cleared. The fault duration is set to be 0.9–1.3 s. In Fig. 6 the active power delivered by the proposed system is about 1.867 times to the conventional one though it suffers from disturbances, similarly, the reactive power absorbed is quite lesser i.e. about 2.95 times than that of conventional one in Fig. 7.

5 Observational Analysis

The observational analysis of the study has been shown in Table 3.

Table 3 Observation analysis of replaced system with conventional in terms of active and reactive power

During healthy condition		During L-G fault condition	
System I	Replaced system II	System I	Replaced system II
$P = 3.458 \times 10^4$ W	$P = 6.443\times 10^4$ W	$P = 3.447 \times 10^4$ W	$P = 6.435 \times 10^4$ W
$Q = 1.37 \times 10^4$ W	$Q = 4660$ W	$Q = 1.378 \times 10^4$ W	$Q = 4671$ W
$\Delta P = 2.985 \times 10^4$ W	% of increase = 46.32%	$\Delta P = 2.988 \times 10^4$ W	% of increase = 46.43%
$\Delta Q = 1193$ W	% of decrease = 19%	$\Delta Q = 1177$ W	% of decrease = 19.61%

6 Conclusion

Thermoelectric Generators (TEG) are integrated with solar PV system in order to process the lost heat by thermoelectric effect. The conversion of light energy into electricity by photoelectric effect and converting heat into electricity by thermoelectric effect combinedly generate a significant amount of power from solar PV array. Hence this technique is implemented on conventional DG. In the proposed SPV-TEG-WES based system, about 45–50% more active power is delivered to the system while about 67–70% lesser reactive power is absorbed than that of conventional SPV-WES. The proposed system is studied on several constraints like active power, reactive power, and solar power. The entire system is modeled, studied, analyzed and validated using MATLAB/Simulink environment. The combined PV-TEG has shown a greater impact on traditional Microgrid giving rise to higher active power delivery to the system, lower reactive power absorbance. Hence the TEG integration is found to be very fruitful to the conventional hybridization where solar PV array is employed. The work can be extended to experimental verification with the theoretical determined results and thereafter the conventional system can be integrated with the TEGs for significant extraction of power from the solar PV array.

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