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Design of Stand-alone Thermoelectric Power Generation System for Marine Engine Exhaust System

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Abstract— Due to increasing energy costs and environmental concerns, there has been strong motivation for using waste heat recovery technologies in Marine application to increase the overall system efficiency. The paper proposes an energy harvesting system that could be applied to marine engine exhaust system, based on thermoelectric power generator (TEG). The TEG system is designed based on string-converter system concept in order to overcome the challenges of mismatch power losses and difficulties of operating all TEGs at their Maximum Power Point (MPP) for large-scale application. In this paper, a string converter system based on Single Ended Primary Inductor Converter (SEPIC) power converter is proposed. The effectiveness of the proposed TEG system in generating electrical power from waste heat under various temperature gradient scenarios was verified using a two-string power converter system prototype. Experimental results clearly show that the proposed converter system is able to extract 24% more power from the waste heat source compared to a conventional single converter system.

Keywords—Thermoelectric Generator; P&O MPPT Algorithm; SEPIC; Boost converter; String converter system; Li-ion battery charging.

I. INTRODUCTION

There have been strong interests in applying waste heat recovery technologies in Marine application due to the significant amount of waste heat generated from the Marine power system. Thermoelectric power generation is one of the waste heat technologies that have been under active research. TEGs are highly reliable semiconductor devices [1], which could be easily installed across any thermal gradient to generate pollution free electrical energy [2]. Due to the presence of many potential waste heat recovery locations with consistent temperature (Table I) and unlimited supply of sea water for cooling the TEG system, there is significant potential for applying TEG system in Marine applications. As shown in [3] thermoelectric power generation is able to provide more than 2.5% improvement in the Brake Specific Fuel Consumption (BSFC) of Marine Engines.

In this paper, a TEG system is targeted to be applied to the engine exhaust system due to the high amount of waste heat energy generated from the system, which is 25% of the fuel input for a 69,720 kW engine, i.e. 42.58g/kWh [4]. To increase the overall system efficiency, this large amount of waste heat can be extracted to power electrical systems within the Marine

power system via thermoelectric power generation. In general TEG converts heat, which causes the temperature difference (ΔT) between the hot side (e.g. exhaust gas) and the cold side (e.g. sea water), directly into electrical energy based on the Seebeck effect. A TEG system consists of modules that are connected in series to form a string to attain the required output voltage, and strings are connected in parallel to obtain the required output power [6].

To ensure optimum power generation of the TEG system, the temperature difference between the hot side and the cold side of TE modules needs to remain consistent as the TE module has optimum efficiency at a ΔT of at least 50°C or higher. However, for large scale applications of TEG system such as Marine engine exhaust system, the temperature of waste heat may vary and the ΔT may not be consistent. This would cause the voltage generated by each TEG string to vary. Under such condition, if the TEG strings are directly connected to the loads, their operating points would be set by the load impedance, causing the TEGs not able to generate their individual maximum power. As a result, a DC-DC converter controlled using Maximum Power Point Tracking (MPPT) algorithm is generally applied to TEG system to ensure the TEGs are always operated at MPP. Nevertheless, for large scale application such as marine engine exhaust system, single power converter system is not sufficient to control a TEG system with multiple strings of TEG modules. This is because the voltage difference generated by each TEG string (due to different temperature along the exhaust pipe) cause mismatch power losses, causing difficulty to operate each TEG string at its MPP [13].

Considering the low efficiency of TE module (5-7%), proper converter system design has to be developed in order to ensure optimum thermoelectric power generation. Therefore, to overcome the abovementioned challenge, a string converter

TABLE I. EXAMPLE OF WASTE HEAT SOURCES IN A SHIP [5]

Heat Source	Medium	Temp.(°C)
Electrical generating unit	Flue gas	340
Incinerator	Flue gas	340
Main engine exhaust after boiler	Flue gas	210
Main engine scavenge air cooling	Air	162
Excess steam from boiler	Steam	159
Main engine cooling water	Fresh water	83
FW generator unit, boiling water	Fresh water	61
Lubricating oil cooler	Lubrication oil	49
FW generator unit, condenser	Salt water	37

Fig 1: Proposed String Converter Thermoelectric Power Generation System

system configuration for TEG system was proposed in [14]. As shown in Fig. 1, each TEG string is equipped with a MPPT controlled power converter. Each TEG string needs to be placed along the isothermal line on the exhaust system and respective converter would ensure that all TEG modules in that particular string are controlled to generate maximum power [14]. Earlier studies proposed a string converter system based on four-switch buck-boost topology [14]. Even though four-switch buck-boost topology exhibit advantages, such as continuous input current and capability to track optimum MPP at all operating conditions (dynamic load and temperature variation), the system requires complex control strategy to ensures smooth transition among different operating modes (boost, buck and buck-boost), complex control circuitry and low efficiency of power converter when operated in buck-boost mode [20]. In order to overcome these challenges and develop a high efficient power generation system for TEG system for large-scale application with simple control strategy, a string converter system employing non-isolated single switch power converter topology is explored in this study.

In this paper, a string converter system based on Single Ended Primary Inductor Converter (SEPIC) power converter controlled using Perturb & Observe (P&O) optimization algorithm is proposed. Fig.1 shows the block diagram of a complete TEG system, which the harvested energy is stored to the Li-ion battery using Synchronous Switch-Mode battery charger and the stored energy can be used to supply power to other electrical systems within the selected platform. This paper is organized as follows. Section II explains about the developed simulation model of TE module, selection of suitable power converter for designed power converter system and operating principle of the selected MPPT algorithm. Simulation analysis of the proposed string conversion system is discussed in Section III whilst the experimental validation of the proposed system is explained in Section IV. Finally, the conclusion is discussed in Section V.

II. TEG MODULE, MPPT ALGORITHM & DC-DC POWER CONVERTER

A. Thermoelectric Generator simulation model

In this work, simulation model of TE module based on experimental data was developed. The common electrical

equivalent circuit of TE model [6], [15] was not used because the electrical equivalent circuit model does not characterize the exact electrical behavior of TEG based on the variations of source temperature or duty cycle of power converter. Also, the model cannot be used to check the accuracy or effectiveness of the control algorithm.

The TE model was developed based on the experimental data of commercial TE modules, which was tested using the test-rig shown in Fig.8. Various types of TEG modules were tested to obtain the voltage and current characteristics under different temperature gradients (Fig 2). The experimental data is loaded into Matlab, which the optimization and curve fitting tools are utilized to create the model. The TE model consists of 2 inputs (input feedback current and temperature difference) and 1 output (output voltage generated by TE model in the particular operating conditions). By using this model, the TEG operating point could be easily identified and, by comparing the operating point and MPP of TEG, the effectiveness and accuracy of MPPT algorithm could be evaluated.

B. P&O MPPT Algorithm

Considering the consistent behavior of exhaust gas temperature along the isothermal line, a simple but reliable algorithm, P&O algorithm, is selected for controlling the proposed converter system [16].

The algorithm operates by perturbing the operating point of TEG by a small value and comparing the output power of TEG at the current operating point and previous operating point. If there is increase in power, it means that the operating point moved towards MPP and the following perturbation should be

Fig. 2. V-I characteristics of TEG

kept in the same direction to reach MPP. If there is decrease in power, it means that the operating point moved away from MPP, and the next perturbation should be reversed. This process is repeated periodically until MPP is reached. Under steady state condition, the operating point of the TEG system will oscillate about the MPP [16], [21].

C. Power Converter Selection

The main requirement for the dc-dc power converter used in MPPT application is low input current ripple for precise MPP tracking [6], [8]. Compared to other power converter topologies, Buck converter has pulsating input current and requires additional filter capacitors at the input side whereas Boost converter and its derived topologies has low ripples at the input side, which is advantageous for MPPT [8] [9]. Power converter topologies such as, Buck-Boost, SEPIC, Cuk and Zeta are capable of providing load voltages higher and lower than the input voltage (buck-boost). However, for Buck-Boost and Zeta topologies, the input current is discontinuous because the switch is located in series with the TEG string. This causes great harmonic distortion, hence producing high input current ripple and noise problems. SEPIC and Cuk topologies have non-pulsating input current which minimizes the electromagnetic interference (EMI) and reduces the need for additional filters [8]-[9]. Both topologies use same number of components, subject the same stresses to the switches and offer similar efficiency. But, for SEPIC converter, the coupling capacitor voltage must follow the input voltage, whereas in Cuk converter, it is the sum of input and output voltage. So the coupling capacitor size can be smaller in SEPIC [9]. Thus among the different buck-boost topologies, SEPIC power converter exhibits desirable characteristics for MPP tracking.

Based on the study, Boost [11] and SEPIC topologies have continuous input current, which is one of most important requirement of power converters used in MPPT application. A comparison study was performed to determine the suitable converter for thermoelectric power generation.

The design parameters of both power converters are shown in Table II [12], [17]. Based on the simulation analysis, followed by verification using prototype of power converters, it was observed that Boost converter is not able to track MPP at all dynamic loads (Fig. 4) [comparing power generated by TEG (Fig.4) and power curve of TEG (Fig 11)], whereas SEPIC is able to track MPP with dynamic loads at the output side.

Block diagram of the experimental setup to track MPP of TEG is shown in Fig 3. TEG voltage and current are measured using sensors and the sensed values are used to implement P&O algorithm. MPPT algorithm was implemented in real time with the help of dSPACE1103. The system calculates the PWM signal using the proposed MPPT algorithm and generates the PWM signal, to drive the IGBT of power converter using opto-coupler.

The following section explains the reason for the tracking issue faced by boost converter. From Fig. 3, it can be written that,

$$V_R = RI_R \quad (1)$$

Calculating the static gain (G) of DC-DC converter from Fig. 3, we get

$$G = \frac{V_R}{V_{TEG}} \quad (2)$$

$$G = \frac{I_{TEG}}{I_R} \quad (3)$$

substituting V_R from (2) and I_R from (3) in (1), we get,

$$\frac{V_{TEG}}{I_{TEG}} = \frac{R}{G^2} \quad (4)$$

V_{TEG}/I_{TEG} is the effective resistance of the TEG string across terminals A and B in Fig.3. From (4) it can be seen that, DC-DC converter emulates a variable resistance, whose value can be varied as a function of G [7].

$$V_{TEG} = \frac{R}{G^2} I_{TEG} \quad (5)$$

TABLE II: SEPIC AND BOOST CONVERTER COMPONENT VALUES

Component	Value for SEPIC	Value for Boost
Frequency	10 kHz	10 kHz
Input Capacitor	100 μ F, 63V	470 μ F, 50V
Coupling Capacitor	200 μ F, 100V	NIL
Output Capacitor	1000 μ F, 63V	470 μ F, 40V
Inductor	2mH, 2.4A	0.8mH, 2A
Diode	STPS10L25D	STPS10L25D
IGBT	IRGPC50U	VNP14NV04-E
Opto-coupler Driver	HCPL-3180	HCPL-3180

Fig 3. Block diagram of experimental setup to track MPP

Fig.4.Power generated by Boost converter working in the experimental MPP system with different loads

Fig 5. Duty cycle of Boost converter working in the experimental MPP system with different loads

When (5) is plotted on a V-I plane, a straight line at an inclination angle θ , defined by equation (6) is generated.

$$\theta = \text{atan}\left(\frac{G^2}{R}\right) \quad (6)$$

Substituting value G for boost and SEPIC topology from [7], effective inclination angle θ as a variable dependent on duty cycle can be calculated [10]. Since duty cycle is limited in the range 0 to 1, the effective inclination angle is limited into a range whose boundaries are determined by the selected DC-DC converter [Table III]. On representing Table III graphically, it was observed that the TEG V-I plane could be divided into a MPPT tracking region and non-tracking region, depending on the topology of interfacing power converter.

Comparing the graphs in Fig 6, it can be seen that the tracking region of boost is limited to certain region of V-I plane, so load has to be carefully chosen to ensure the MPP of TEG is within the tracking region. Whereas SEPIC is capable of tracking MPP over the entire V-I plane, which means, it can track MPP at any load or system operating condition, which is an essential requirement in Marine systems, as the loads are dynamic.

Thus, based on the comparison between various DC-DC converters, SEPIC operating in continuous conduction mode (CCM) (Fig. 9) is considered a suitable power converter for the TEG system due to its buck-boost capability without voltage inversion, absence of non-operating region during maximum power point tracking and, most importantly, the low ripple input current in for more precise MPPT.

III. SIMULATION ANALYSIS OF PROPOSED SYSTEM

As explained earlier, a string converter system based on SEPIC topology is proposed to overcome the limited capability of single converter system in operating the TEG system at MPP. Each P&O MPPT controller sets the operating point of the TEG modules in that particular string based on the detected output current and voltage of respective string.

TABLE III: LOAD INCLINATION ANGLE AS A FUNCTION OF CONVERTER DUTY CYCLE

DC-DC Converter	Effective load inclination angle θ	Minimum effective load inclination angle $\theta _{D=0}$	Maximum effective load inclination angle $\theta _{D=1}$
Boost	$\text{atan}\left(\frac{1}{(1-D)^2 R}\right)$	$\text{atan}\left(\frac{1}{R}\right)$	90°
SEPIC	$\text{atan}\left(\frac{D^2}{(1-D)^2 R}\right)$	0	90°

Fig 6. Tracking and non-tracking regions of Boost and SEPIC converter

To verify the effectiveness of the proposed string converter system in extracting maximum power from each TEG string, a four-string (with 10 TEG1-12611-6.0 in each string) 500W thermoelectric power system was modelled in MATLAB/Simulink, which the simulation results of string1 and string4 are shown in Fig. 7. As shown in the figure, the MPPT is initiated at 0.1 second. By comparing the input powers of the converters (Fig 7) with the maximum power generated by TEG string (Table IV), it is clear that the control strategy maintains the operating point of each TEG string at its MPP. Based on the simulation analysis, the P&O algorithm showed good tracking efficiency even for a temperature difference of 40°C between the strings. The string converter has an overall efficiency of 95.30%, when ΔT string1= 150°C, ΔT string2= 130°C, ΔT string3= 120°C and ΔT string4= 110°C.

The second stage of the system includes a PWM control battery charger and a 36V, 15Ah, Lithium-ion battery pack. The charger is controlled using Constant Current- Constant Voltage (CC-CV) algorithm [19]. When the power drawn by the load is lower than the power generated by TEG system, the TEGs are capable of charging battery and supplying load simultaneously. When the power demand exceeds the power generated by TEG, the load draws power from the batteries. The charging and discharging of the battery based on the variation of power demand is shown in Fig 7.

Fig 7. Temperature change, Input Power to the converter and SOC of Battery

TABLE IV. MAXIMUM POWER GENERATED BY 10 TEGs CONNECTED IN SERIES AT DIFFERENT ΔT

Temperature difference (ΔT)	150°C	130°C	120°C	110°C	100°C
Maximum Power generated by 10 TEG modules connected in series (W)	138.6	115	99.1	80.09	63.07

IV. EXPERIMENTAL VALIDATION

A. Experimental setup

Figure 8 shows the hardware setup to verify the effectiveness of string converter system in converting waste heat into electricity from two TEG strings. Temperature difference, ΔT string1=88°C, ΔT string2= 72°C is applied across the two TEG strings, consisting of 4 TEG (TEG1-12611-6.0) modules each, with the help of test rig shown in Fig 8. The TEG strings are connected to the input of SEPIC power

Fig. 8. Prototype of Two-String Thermoelectric Power Generation System

converters, the power converter component specifications are shown in Table II. Under the given operating conditions, SEPIC 1 and SEPIC 2 are operating at an efficiency of 81.23% and 77.87% respectively.

Data acquisition and tracking of MPP TEG string is realized in real time using dSPACE 1103. Voltage sensors (LV 25-P) and current sensors (LA 25-NP) are employed to measure the input voltage and current of TEG string. The measured values are passed on to the P&O MPPT block in Simulink via ADC port of dSPACE controller board. The MPPT block calculates the duty cycle of switching signal, and the PWM switching signal generated is passed through the controller board to drive the IGBT of power converters.

The energy regenerated from waste heat is stored in an 11.1V, 2.6Ah lithium-ion battery pack using Synchronous Switch-Mode battery charger BQ24130EVM [18]. The battery is charged based on CC-CV algorithm.

B. Experimental Results

The experimental results of the power generated by string 1 and string 2 and total power extracted using the proposed system is shown in Fig. 10. Comparing power curve of TEG (Fig.11) to the power generated by TEG (Fig. 10), it is observed that P&O algorithm tracked the maximum power under operating condition (ΔT) successfully with a tracking efficiency of above 98% (calculated with a maximum error of 1.95% (Table V)).

The power extracted by string converter system is stored in a Li-ion battery pack; voltage across the battery and the

charging current flowing into the battery from the power converter system, during the charging process are shown in Fig.12 and Fig.13 respectively. Maximum charging current flows into the battery until the voltage across the battery reaches over charge voltage (11.35V). Once the battery voltage reaches 11.35V, charging current starts to drop and voltage remains constant.

To prove that the string converter system is able to extract more power from the waste heat compared to a single converter system, a SEPIC converter is developed and tested with two parallel TEG strings (ΔT string1=88°C, ΔT string2= 72°C) connected to its input. The power converter is operating at an efficiency of 83.40%.

Fig. 9. Inductor current waveform of SEPIC operating in CCM

The experimental result of power extracted by the single converter system is shown in Fig. 10. The power variation, P_{VAR} (%), the percentage difference between power extracted from waste heat by a string converter system and a single converter system is calculated using the equation,

$$P_{VAR} (\%) = \frac{P_{string}(t) - P_{single}(t)}{P_{single}(t)} \times 100\% \quad (7)$$

where P_{string} and P_{single} are the power extracted by string converter system and single converter system respectively. From Table VI, when temperature difference exists between two TEG strings, proposed string converter system is capable of extracting 24.85% more power from waste heat compared to the conventional single converter system because the proposed system can achieve accurate MPP for each TEG string. Also, the output power stored in the battery pack by string converter system is 20% more compared to the single converter system.

Fig. 10: Experimentally tracking maximum power from TEG using P&O algorithm

Fig. 11: Power curve of TEG string (four TEG modules in series) at different ΔT

Fig. 12: Li-ion battery's battery voltage during charging process

Fig. 13: Li-ion battery's charging current during charging process

TABLE V: COMPARISON OF TRACKING PERFORMANCE OF THE MPPT CONVERTER TO THE MAXIMUM AVAILABLE POWER FROM THE TEG STRING

ΔT (°C)	P_{MAX} (expected maximum power) (W)	P_{MPPT} (Power extracted by MPPT controller) (W)	$P_{VARIATION} = \frac{P_{MAX} - P_{MPPT}}{P_{MAX}}$	
			(W)	(%)
String 1=88	7.66	7.55	0.11	1.45
String 2=72	5.21	5.11	0.10	1.95

TABLE VI: COMPARISON OF POWER EXTRACTED BY STRING CONVERTER AND SINGLE CONVERTER SYSTEM

Power extracted by		Variation in input power $P_{VAR} = P_{string} - P_{single}$		Output power of	
String converter system (P_{string}) (W)	Single converter system (P_{single}) (W)	P_{VAR} (W)	P_{VAR} (%)	String converter system (W)	Single converter system (W)
12.76	10.22	2.54	24.85	10.11	8.42

V. CONCLUSION

In conclusion, a string converter system is required to overcome mismatch power losses and ensure optimum power extraction from TEG modules installed in waste heat sources with wide temperature variation. A two-string converter system was built and tested. The experimental results prove that the proposed string converter system is capable of extracting about 24% more energy from waste heat compared to the single converter system for a temperature imbalance of 16°C between the two strings. Furthermore, based on the comparative study of various single switch power converter topologies, it was evident that SEPIC topology is best suited for TEG power generation applications because of its continuous input current and ability to track MPP at all loads. The future work includes implementing the control algorithm using C2000 microcontroller and increasing the power converter switching frequency to 100 kHz, which will help in reducing the component sizes and the power losses in the system, thereby increasing the efficiency of the power conversion system.

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