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Simulating the Steady State and Dynamic Conditions of an Onshore Three Phase Linear Generator

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Abstract: Sea wave is an alternative renewable energy source that can meet excessive demand for energy throughout the country. The sea waves have high potentials for harvesting wave energy. A three-phase linear generator (TPLG) is an electromechanical energy converter driven by a reciprocating prime mover. It has a simple design and has less mechanical interface. It is used as a device to convert sea waves energy into electrical energy. The core of this paper is to simulate the steady state and dynamic conditions of an onshore TPLG. Two models of the TPLG are analyzed, TPLG-6 and TPLG-18. The performances of the TPLG operation are analyzed in steady state and in dynamic conditions using MATLAB simulation. These graphs of the output terminal voltage, output power, input power, phase current and induced emf are presented. Under the steady state conditions, the efficiencies for TPLG-6 and TPLG-18 are 85% and 94% respectively. However, in dynamic conditions, the efficiencies are 83% and 93% respectively. Finally, the TPLG-18 provides higher efficiency than the TPLG-6.

Keywords: Three Phase Linear Generator (TPLG).

1. Introduction

Malaysia has a long coastline. The South China Sea and the Straits of Malacca surrounded west Malaysia. East Malaysia consists of Sabah and Sarawak, bordered by the South China Sea, the Sulu Sea and the Celebes Sea. The total land area of the country is 330,323 km^2 whereas the population is 31.66 million. The average annual population growth rate is 1.5% (Department of Statistics Malaysia, 2016). Therefore, the energy demand is increasing. The expected energy consumption will reach 4000 MW. Malaysia is heavily dependent on fossil fuels, which are rapidly depleting (Lim, Lam, & Hashim, 2015). Therefore, Renewable Energy (RE) is a good alternative to traditional fossil fuel.

Renewable energy available in Malaysia are biomass, solar, wind, geothermal, hydropower, etc. These RE are clean, safe, cheap and environmental friendly. Among the REs, Marine Renewable Energy (MRE) such as tidal waves energy and sea waves energy are exploitable (Yaakob, Rashid, & Mukti, 2006). Countries having a long coastline should pay more attention to the development of MRE technologies. In 2009, the Malaysian government launched the National Green Technology Policy to ensure that Malaysian will enjoy a good quality of life and living in a healthy environment (Government of Malaysia, 2010; Sandro et al., 2015). It is for this reason that we should put in more effort to do researches on MRE and MRE technologies.

Many types of Wave Energy Conversion (WEC) or linear generator technologies have been designed, experimented and developed. The linear generators can be classified according to their device size, directional wave characteristics, working principles or their placements, namely onshore, near-shore, and offshore. Fig. 1 depicts the location of wave energy converters (Martínez de Alegría, Kortabarria, Andreu, López, & Ceballos, 2013). Among the three locations, onshore devices are easily accessible, and installation and maintenance are easy. However, these linear generators need additional substations to connect directly to the national grid (Hamim, Ibrahim, & Nor, 2014; Hong et al., 2014). The onshore water depth is less than 10 m as illustrated in Fig. 1.

Sea wave is an alternative renewable energy source that can meet excessive demand for energy throughout the country. The sea waves have high potentials for harvesting wave energy. A three phase linear generator (TPLG) is an electromechanical energy converter driven by a reciprocating prime mover. It has a simple design and has less mechanical interface. It is used as a device to convert sea waves energy into electrical energy. The core of this paper is to model the steady state and dynamic conditions of an onshore TPLG. The performances of the TPLG have been examined.

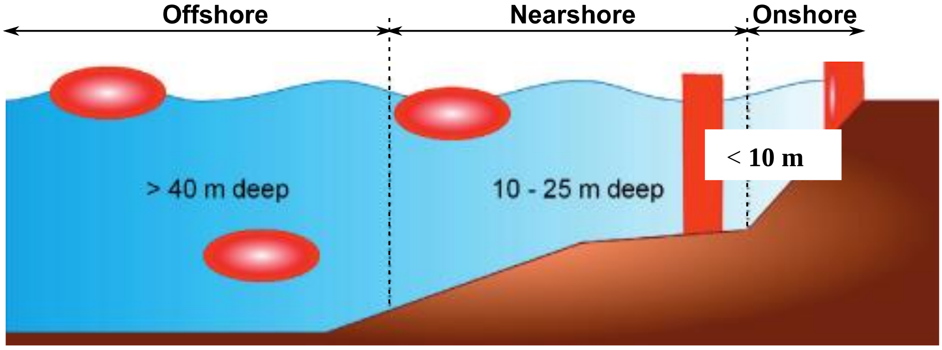

Fig. 1. Location of Wave Energy Converters

2. Methodology

The flowchart for the whole simulation process is shown in Fig. 2.

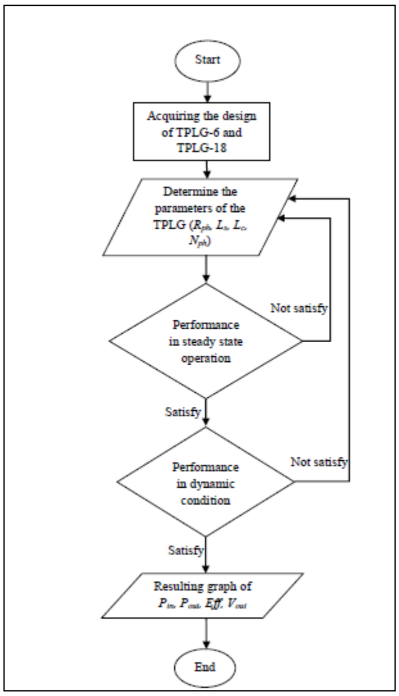

Fig. 2. Flowchart of the Whole Process

Two models of the TPLG are examined, TPLG-6 and TPLG-18. The TPLG-6 is designed to have 6 winding slots and the TPLG-18 is designed to have 18 winding slots. The parameters of the resulting per-phase equivalent circuit of the generators are determined by using FEMM software. The performances of the TPLG operation are analyzed in steady state and in dynamic conditions using MATLAB simulation. In steady state condition, the generator parameters have been calculated. These parameters are phase resistance, synchronous inductances, length of the coil and number of turns per phase. These parameters also have been used for dynamic conditions. Each model has been connected to a load resistor. The load resistor for TPLG-6 is 5 Ω and for TPLG-18 is 7.5 Ω. The input parameters for steady state operation and dynamic operation are shown in Table 1 and Table 2 respectively. The average floater velocity, v_{av} is assumed to be 1.0 m/s. The generator efficiency can be obtained with the assumption of that the power losses in the primary core and mechanical losses are ignored:

$$Eff = \frac{P_{out}}{P_{inp}} x100\% \tag{1}$$

Table 1. Input parameters for Steady State Operation

Model	TPLG-6	TPLG-18
Length of coil, L_c (m)	1.079	0.6428
Number of phase, N_{ph} (turns)	276	240
Resistance per one km of AWG wire, R_{wpkm} (Ω)	3.277	3.277
Phase resistance, R_{ph} (Ω)	1.0	0.5

Table 2. Input parameters for Dynamic Operation

Parameter	TPLG-6	TPLG-18
Load resistance, R_L (Ω)	5.0	7.5
Synchronous inductance, L_s (H)	0.059	0.213
Phase resistance, R_{ph} (Ω)	1.0	0.5
Secondary speed amplitude, u_m (m/s)	1.57	1.57
Voltage constant, K_E (V.s/m)	326.6	103.2
Pole pitch, τ_p (m)	0.030	0.088

The performance characteristics can be represented as graph of P_{in}, P_{out}, V_{out}, I, and *Eff* versus load resistance. Fig. 3 shows the Simulink model of TPLG-6 and Fig. 4 shows the Simulink model of TPLG-18. The results of the simulation will be plotted.

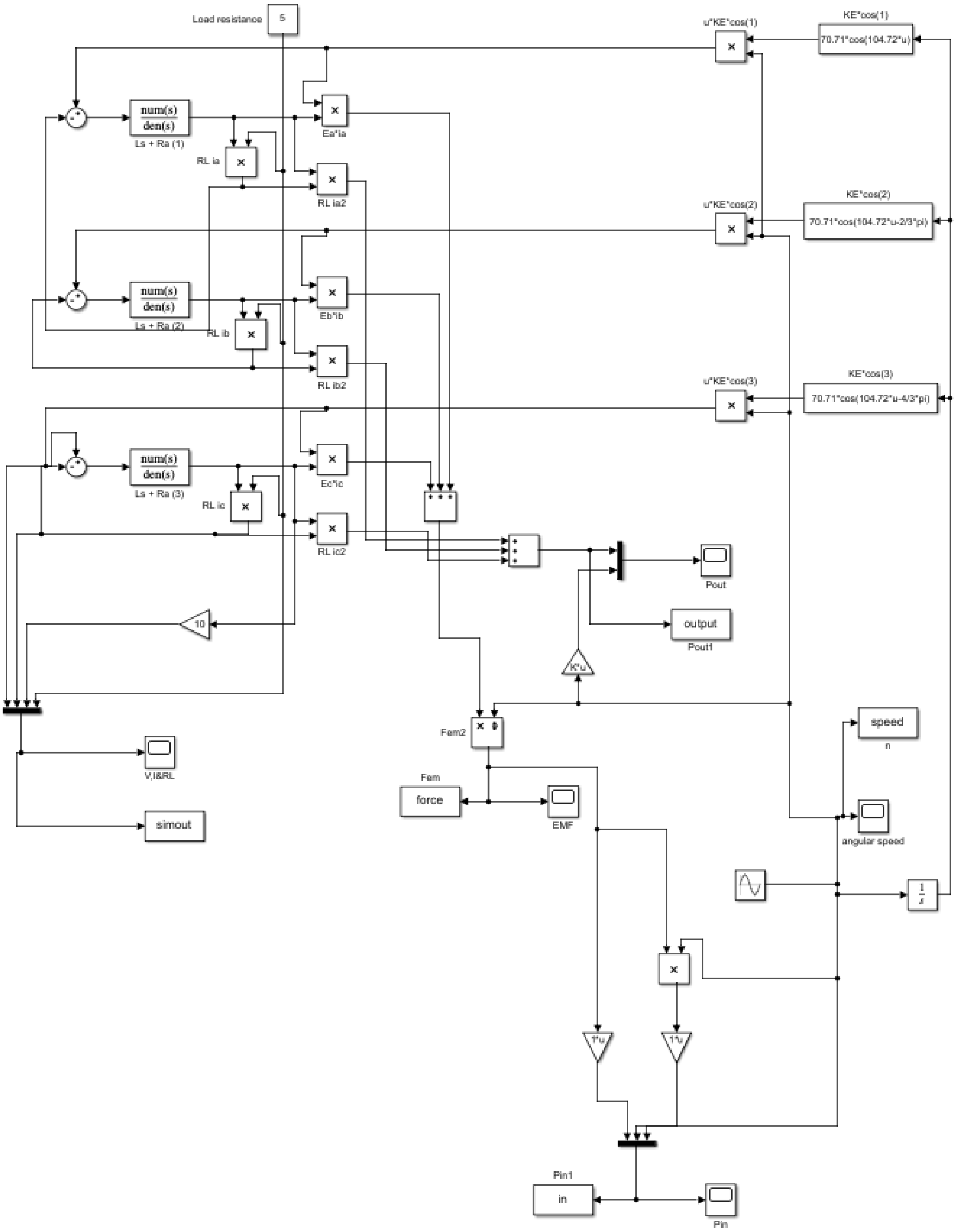

Fig. 3. Simulink Model of TPLG-6

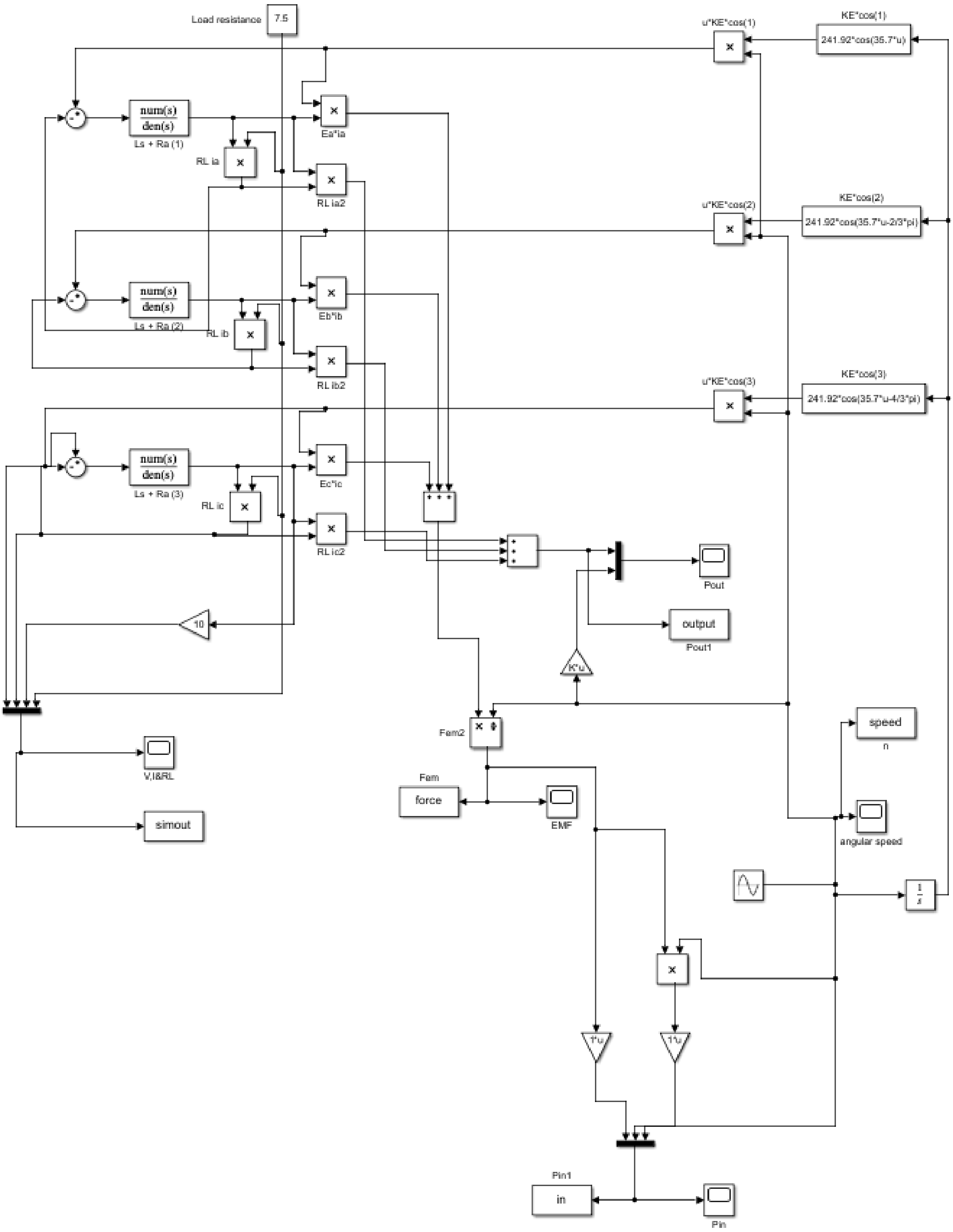

Fig. 4. Simulink Model of TPLG-18

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3. Results & Discussions

3.1 Simulation Results for TPLG Under Steady State Condition

Steady state operation was performed by using Matlab software. To analyse the TPLG performance at constant speed operation or steady state condition, the single phase circuit of the generator is taken into account. It consists of synchronous inductance L_s, phase resistance R_{ph}, and load resistance R_L. In both models, the permanent magnet is replaced with air and the model is supplied with the rated current in phase one and zero current in the other two phases. The graph in Fig. 5 and Fig. 6 give the expected outcomes and Table 3 shows the corresponding data for steady-state operation for TPLG-6 and TPLG-18.

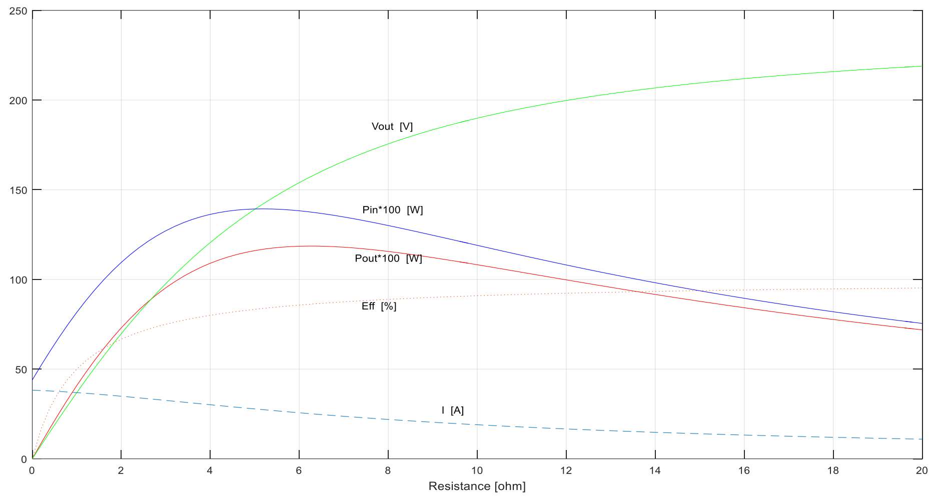


Fig. 5. Performance Characteristics of TPLG-6 as the Function of Load Resistance, R_L

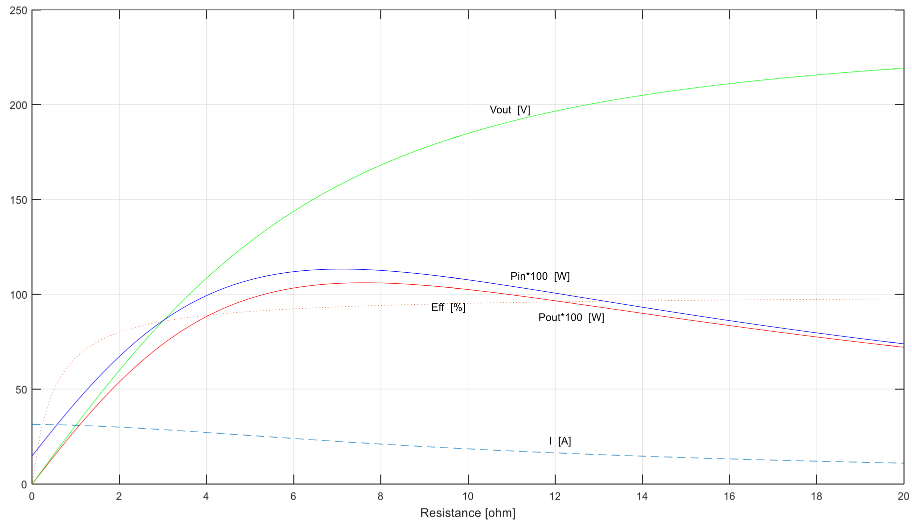


Fig. 6. Performance Characteristics of TPLG-18 as the Function of Load Resistance, R_L.

Varying load resistance, R_L in the range from 0 Ω until 20 Ω, the maximum output power at steady-state is measured. From the Fig.5, the maximum output power, P_{out} is 11.8 kW, the maximum current, I_a is 25 A, and the maximum output voltage, V_{out} is 157 V when the generator is loaded with resistive load, R_L of 5 Ω. By increasing the resistance value after 5 Ω, the output power, input power, and current decreases. Therefore, at resistive load, the power is directly proportional to the square of the voltage and inversely proportional with resistance. The maximum input power, P_{in} is 13.9 kW. Based on Eq.(1), the efficiency for TPLG-6 is 85%.

Referring to Fig.6, the range of R_L is varied from 0 Ω until 20 Ω. The maximum output power, P_{out} = 10.6 kW, the maximum current, I_a = 22 A, and the maximum output voltage, V_{out} = 164 V when the generator is loaded with resistive load, R_L of 7.5 Ω. When the load resistance exceeds 7.5 Ω, the output power, input power, and current decrease. This establishes the same fact that at resistive load, power is inversely proportional with resistance. The maximum input power, P_{in} = 11.3 kW and the efficiency for TPLG-18 is 94%. The results for the steady-state condition is summarized and shown in Table 4.

Table 3. Data for both TPLG-6 and TPLG-18 Steady State Operation

Parameter	TPLG-6	TPLG-18
Frequency, f (Hz)	16.67	5.68
Induced phase voltage, E_{ph} (V)	70.71	230.94
Phase resistance, R_{ph} (Ω)	1.00	0.50
Synchronous inductance, L_s (H)	0.059	0.213

Table 4. Performance Characteristics at Steady State Conditions

Parameters	TPLG-6	TPLG-18
Input power, P_{in} (kW)	13.9	11.3
Output power, P_{out} (kW)	11.8	10.6
Efficiency, Eff (%)	85	94
Phase current, I_a (A)	25	22
Output voltage, V_{out} (V)	157	164
Load resistance, R_L (Ω)	5.0	7.5

3.2 Simulation Results for TPLG Under Dynamic Condition

In this study, both models of three phase linear generator are simulated. The sea wave is assumed to be sinusoidal, the winding inductance is constant, and the TPLG terminals are connected to a resistive load. A simulation was carried out to operate the TPLG in dynamic condition. The model was developed in Matlab Simulink and these are shown in Fig. 3 and Fig. 4.

The maximum speed of wave, is assumed to be 1.57 m/s and the frequency for TPLG-6 is 16.67 Hz while the frequency for TPLG-18 is 5.68 Hz. The simulation results of TPLG-6 are shown from Fig. 8 until Fig. 10. Fig.7 shows the dynamic characteristic of input power, P_{in}, electromagnetic force, F_{em}, and speed versus time. The graph shows that the sinusoidal characteristics due to the TPLG operated at sinusoidal speed, as shown in Fig. 8. The maximum input power, P_{in} of TPLG-6 is 18.2 kW and from the Fig .9, the graph shows that the maximum output power, P_{out} of TPLG-6 is 15.1 kW. Therefore, the efficiency of the TPLG-6 is 83%.

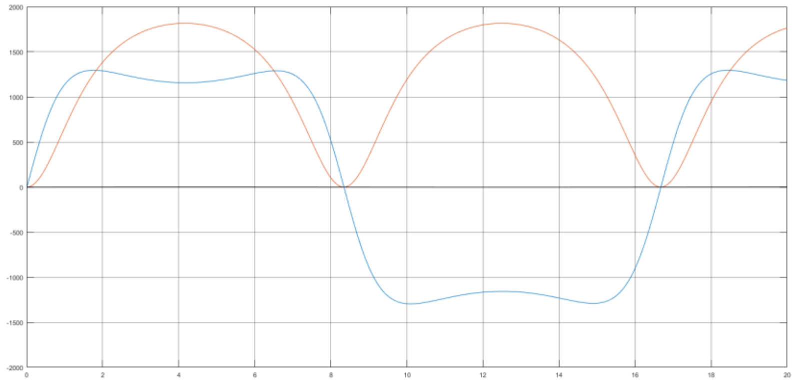


Fig. 7. Dynamic characteristics of input power, electromagnetic force and speed against time for TPLG-6.

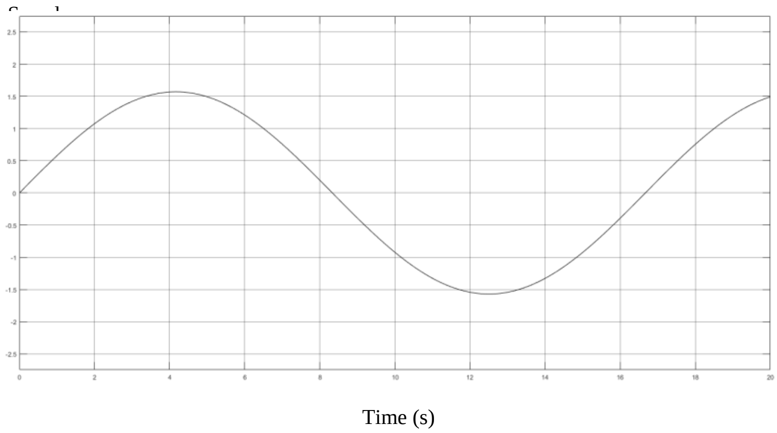


Fig. 8. Speed versus time for TPLG-6.

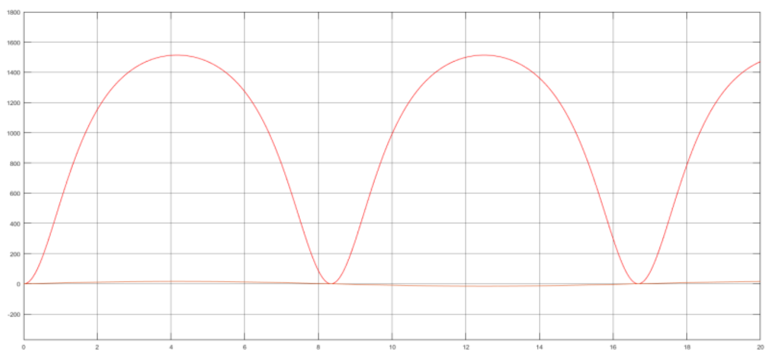
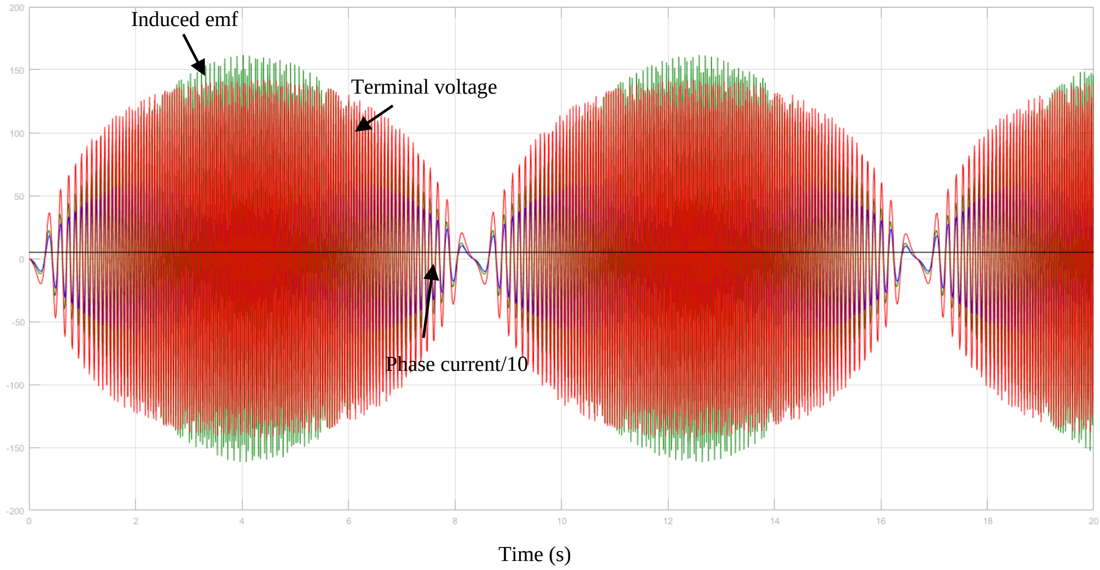
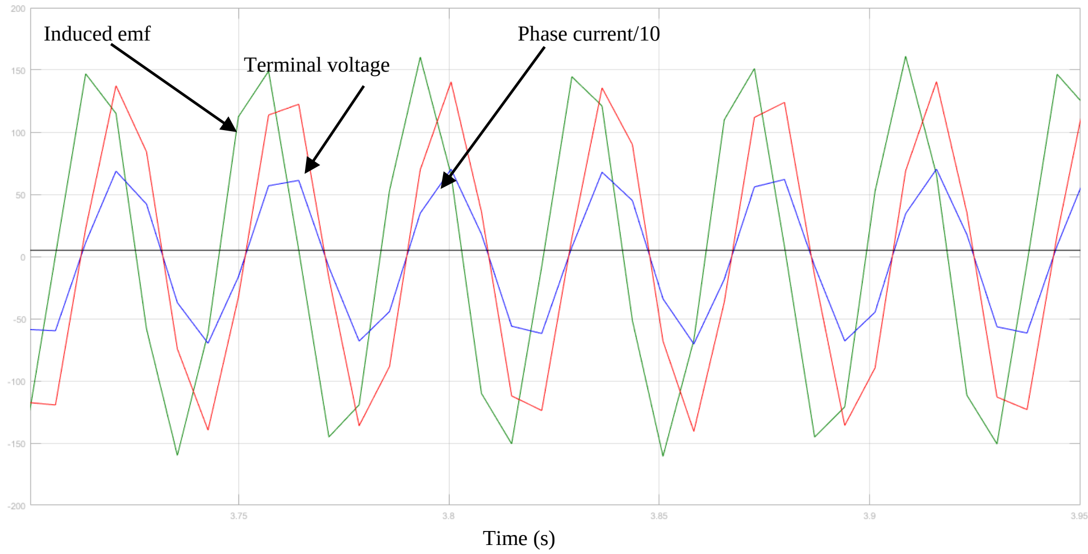


Fig. 9. Output power characteristic versus time for TPLG-6.

The graph in Fig.10 shows the induced emf, terminal voltage, and phase current over time for TPLG-6. The value of induced emf is 162 V, the value of terminal voltage is equal to 142 V, and the value of phase current is 7.1 A.



(a)



(b)

Fig. 10. Terminal voltage, induced emf and phase current versus (a) time interval (0s – 20s), (b) time interval (3.7s – 3.95s) for TPLG-6.

For analysis purpose, the TPLG-18 characteristics of input power, electromagnetic force, and speed versus time graph are shown in Fig. 11. The output power characteristic is shown in Fig.13. The maximum input power is 15.3 kW and the maximum output power is 14.3 kW. The efficiency of the TPLG-18 is 93%.

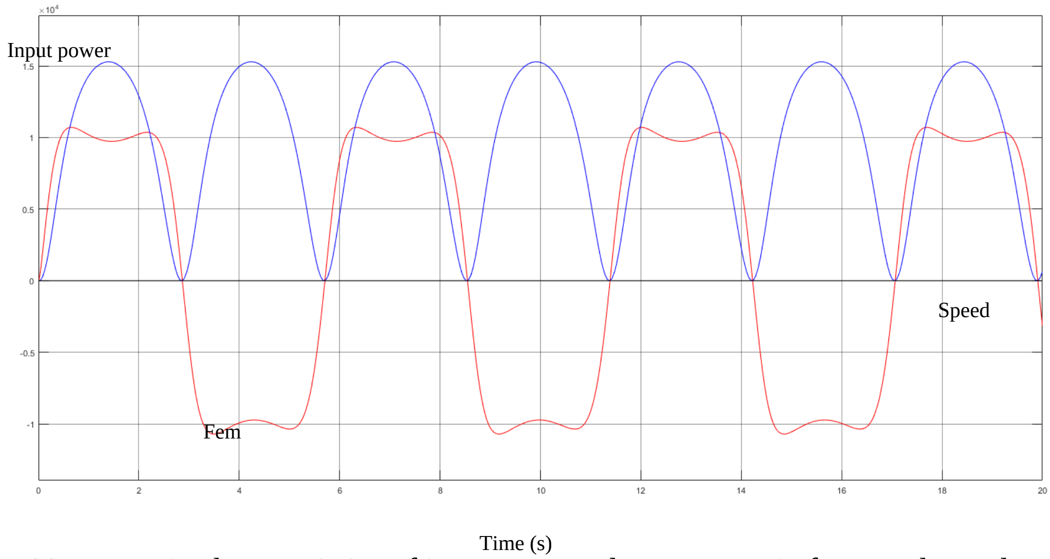


Fig. 11. Dynamic characteristics of input power, electromagnetic force and speed against time for TPLG-18.

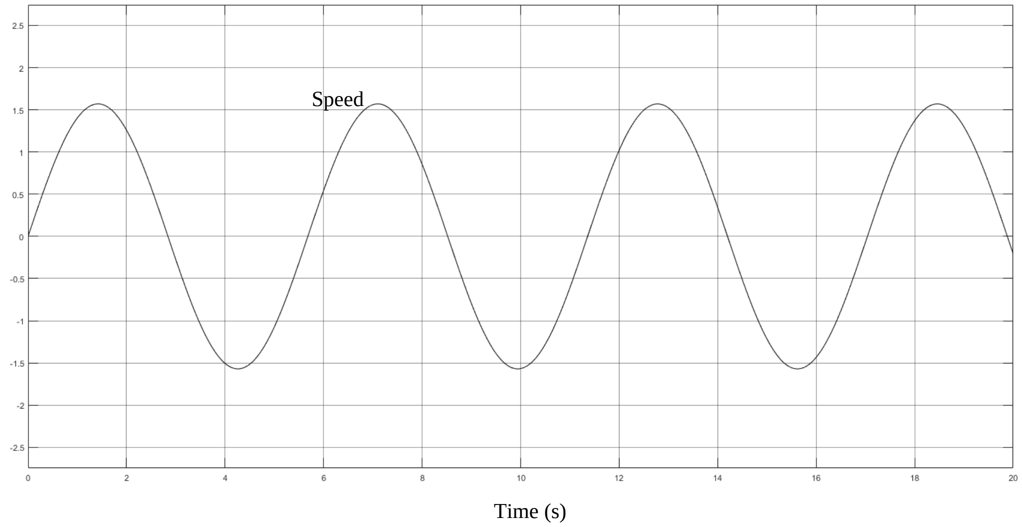


Fig.12.Speed versus time for TPLG-18.

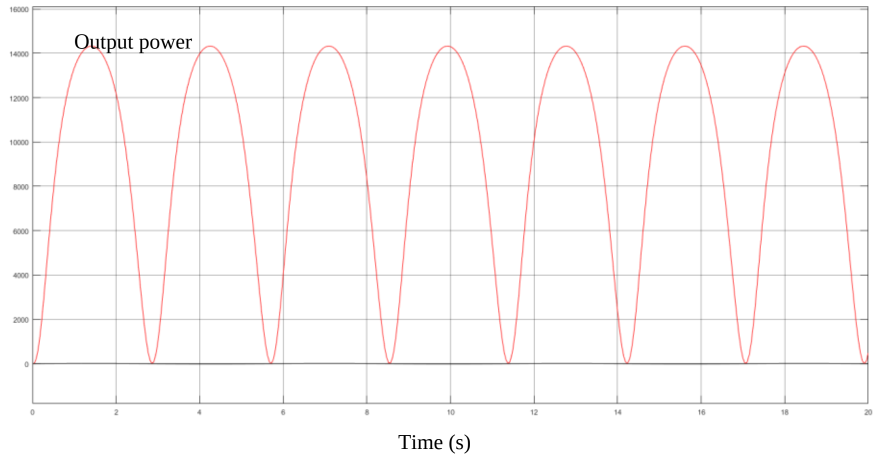
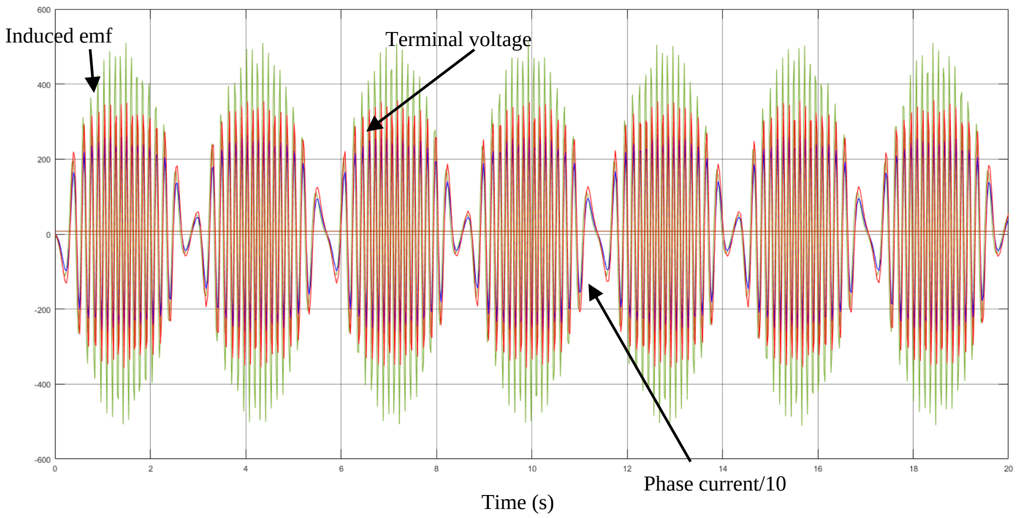
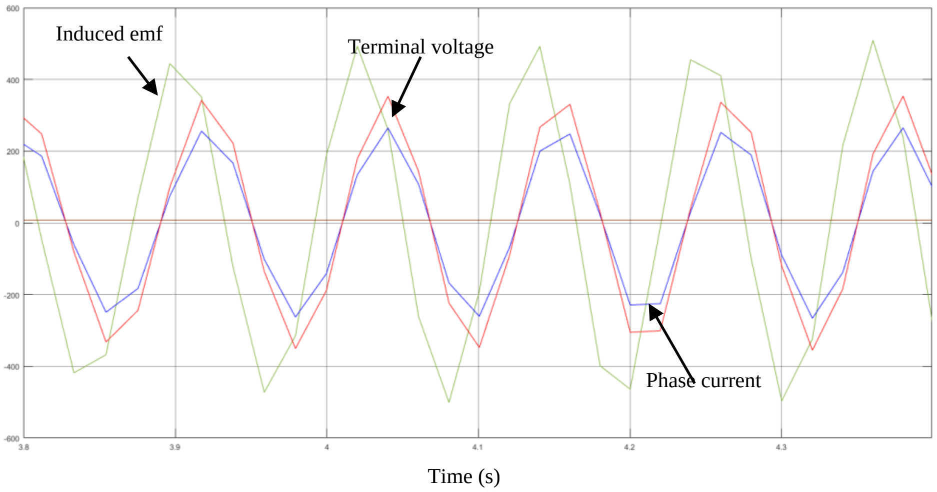


Fig.13.Output power characteristic versus time for TPLG-18.

Fig.14 depicts the graph of induced emf, terminal voltage, and phase current versus time. The resulting induced emf is 512.2 V, the terminal voltage is 356 V and the phase current is 26.7 A.



(a)



(b)

Fig.14. Terminal voltage, induced emf and phase current versus (a) time interval (0s – 20s), (b) time interval (3.8s – 4.4s) for TPLG-18.

Table 5 shows the results of the overall dynamic performance for both TPLGs. Referring to Fig. 10 and Fig.14, the terminal voltage and current are in phase as the linear generator is loaded with pure resistor load. Both speeds are shown in Fig. 8 and Fig. 13 where they are initially zero. As the TPLG begins to move along the z-axis, it is noticeable that the TPLG begins to generate power. Therefore, the induced emf is generated. The TPLG-18 is much better than TPLG-6.

Table 5. Performance Characteristics at Dynamic Conditions

Parameter	TPLG-6	TPLG-18
Input power, P_{in} (kW)	18.2	15.3
Output power, P_{out} (kW)	15.1	14.3
Efficiency (%)	83	93
Induced emf (V)	162	512.2
Terminal voltage (V)	142	356
Phase current (A)	7.1	26.7

4. Conclusion

Both TPLG models are studied and analysed in steady state and dynamic conditions. Under the steady state conditions, the efficiencies for TPLG-6 and TPLG-18 are 85% and 94% respectively. However, in dynamic conditions, the efficiencies are 83% and 93% respectively. Each model has been connected to a load resistor. This efficiency is calculated when the three phase linear generator is connected to a load resistance. The TPLG-18 provides higher efficiency than the TPLG-6. Finally, the objectives are achieved and it gives sufficient results.

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