Modelling and Analysis of Oscillating Water Column Based Wave Energy Converter with Compressed Air Energy Storage system

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***Abstract*—Using Wave Energy Converters as Distributed energy resources gained significant interest nowadays. A recent article from the US National Renewable Energy Laboratory introduced a concept called Distributed Embedded Energy Conversion Technology (DEEC-Tec). In this work a wave energy converter, with compressed air energy storage system and Oscillating Water Column principle, is proposed to be used as a DEEC-Tec. The proposed device addresses power quality issues associated with OWC devices. A Laboratory scale device was developed and tested. The device worked properly, however the produced output was low and recommendations to improve the device are given.**

Keywords—Wave Energy Converter, DEEC-Tec, OWC and CEAS

I. Introduction

Distributed energy resources to meet future energy needs have gained significant momentum in the recent past. Recent article by US National Renewable Energy Laboratory highlights the value of distributed and flexible wave energy converters [1]. This type of resource is called Distributed Embedded Energy Conversion Technology (DEEC-Tec) and placed across the ocean to increase redundancy, resilience, and easier installation.

Multiple small scale Wave energy converters (WEC) are put together to form a DEEC-Tec structure. In the literature, several wave energy converter technologies are proposed. These WEC can be categorized, based on the deployment location, as onshore or offshore devices. Onshore devices are deployed on shoreline. Energy density on shore is less compared to offshore. However, onshore devices are preferred for their low initial investment requirement and easy maintenance [2]. Therefore, onshore wave energy converters are suitable candidates for DEEC-Tec structure development. Oscillating water column (OWC) and Over Topping (OT) device are the main two principles used in onshore wave energy converter developments [2]. However, OWC is the most promising technology, and it can be built at different sizes and power ratings. Further, recent research studies show that OWC is a mature technology compared to other wave energy converter technologies. Therefore, in this study, OWC is evaluated for the development of DEEC-Tec.

When any wave energy converter is connected to the grid the output power from OWC must meet the power quality requirements. However, most of the wave energy converters show power quality issues when they are connected directly to the grid [3]. Flicker is one of those main power qualities issues [4],[5]. This is the major problem with OWC as well. The pulses produced by OWC can vary from zero to several megawatts [6]. Several papers have addressed this problem and suggested using storage technologies to smooth the output wave [6],[7],[8]. Flywheels, accumulators, batteries accumulators and super capacitors are commonly used in wave energy converters as storage technologies [12]. Battery energy storage system (BESS) [7] and Super Capacitor Energy Storage System (SCES) [8] are employed with OWC to eliminate the power quality issue in OWC devices. Battery storage technologies and super capacitor energy storage technologies suitable for short term energy storage applications. However, these technologies are less feasible for bulk and long-term energy storage applications. Moreover, battery life is at high risk due to the high cyclic nature of sea waves [9].

In this work a wave energy converter with compressed air energy storage system is proposed to solve power quality problems in OWC. The proposed device is developed by modifying the OWC in such a way that the device can produce compressed air and store it in a storage tank. Then the compressed air can be used to produce the desired output power. Multiple of this device can be integrated together to form a DEEC-Tec structure.

This paper is organized as follows. Section II presents the working principle of the developed device. Section III provides the mathematical modelling of the proposed device. Numerical analysis, results and discussion are presented in section IV. Conclusion of the paper is presented in section V.

II. Proposed Wave energy converter

The proposed WEC is made up of several mechanical components. This mechanical device includes a floating buoy, pneumatic pump, a compressed air storage tank and a compressed air turbine with generator. Figure. 1 below shows the working principle of the device.

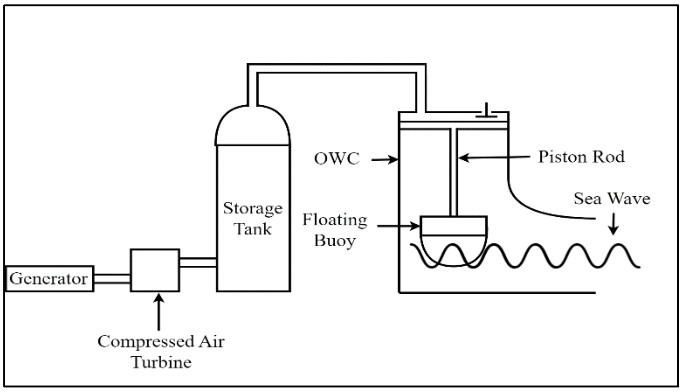

Figure 1 Schematic diagram to show the Working Principle of the Proposed Device

In the proposed device the floating buoy/floating body moves up and down due to the ocean waves. This floating buoy is connected to the piston via piston rod and the piston moves inside the OWC cylinder. This whole setup acts as a pneumatic pump and here after it will be refered as OWC-Pneumatic Pump. Upward motion of this pump will pump the air into the storage tank. Therfore, the continious sea wave motion can pump the air continiously into the storage tank/ gas accumulator. The air is stored at high pressure inside the storage tank. Then this high pressure air is used to drive an air turbine. The air turbine is connected to an electric generator. This can be used produce electricity.

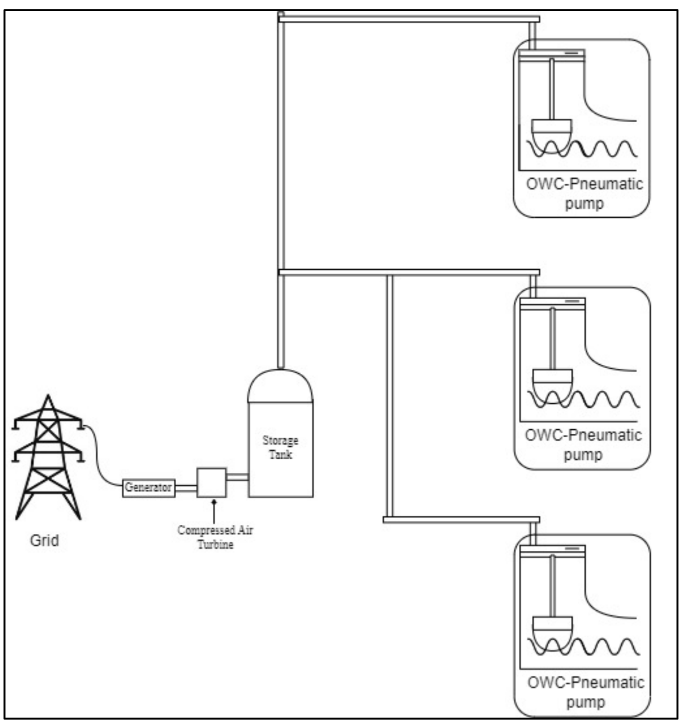

Figure 2 Connecting multiple small WEC together to form a DEEC-Tec structure.

Figure 2. Illustrates how multiple small OWC-Pneumatic pumps can be used to build a DEEC-Tec structure. These OWC-Pneumatic pumps can be modified at different sizes based on the available wave energy and distributed along the coast. Further the shape of the floating buoy can be optimized to increase the wave to air compression efficiency.

III. THEORIES AND MODELING

A. Incident Wave power

Characteristics of sea waves can be represented by their height and length, and the water depth over which they are propagating. These parameters can be used to theoretically estimate any other wave characteristics such as wave energy, power, and velocity. Estimating wave energy is important to analyze the wave energy converter. The total energy contained in a wave consists of potential and kinetic energy.

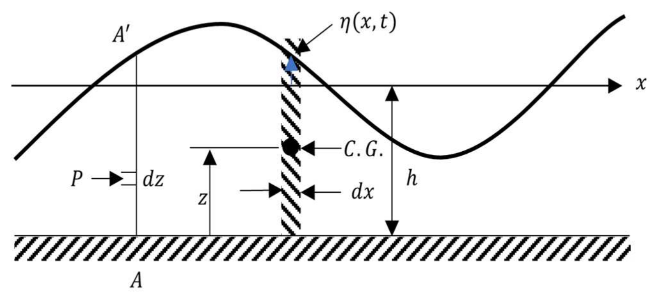

Figure 3-Regulaer wave schematic to estimate the wave energy

Regular sea waves can be considered as sinusoidal waves as illustrated in [10 Fig. 2]. The potential energy, d(PE), of a small water column with mass dm can be expressed based on fundamental physics as:

$$d(PE) = dmg\bar{z} \tag{1}$$

where $\bar{z}$ - height to the center of gravity of the mass and g is gravitational acceleration.

The average potential energy over a wavelength of L for a progressive wave can be calculated as:

$$PE_{avg} = \frac{1}{L}\int_{x}^{x+L} dmg\bar{z}.dx \tag{2}$$

Solving this gave the following equation, where H is the height of the wave and p is sea water density

$$PE_{avg} = \frac{pgH^2}{16} \tag{3}$$

Kinetic energy associated with small mass moving water particles can be estimated as:

$$d(KE) = dm\,\frac{(u^2+w^2)}{2} = pdx\,dz\,\frac{(u^2+w^2)}{2} \qquad (4)$$

where u, w are horizontal and vertical velocities of wave particles respectively. Then the average kinetic energy per unit surface area can be calculated by integrating over the depth and length of the wave:

$$\overline{KE} = \frac{1}{L}\int_x^{x+L}\int_{-h}^{\eta} p\,\frac{(u^2+w^2)}{2}\,dx\,dz \qquad (5)$$

where [10]:

$$u = \frac{H}{2}\sigma\frac{\cosh k(h+z)}{\sinh kh}\sin kx\,.\sin\sigma t$$

$$w = \frac{-H}{2}\sigma\frac{\cosh k(h+z)}{\sinh kh}\sin kx\,.\sin\sigma t$$

where h is water depth, σ is the angular frequency of the wave, H is the height of the wave.

The kinetic energy of the sea waves per unit surface area for a wave can be given by the following expression:

$$\overline{KE} = \frac{pgH^2}{16} \qquad (6)$$

The total available energy is given by

$$E = \overline{KE} + \overline{PE} = \frac{pgH^2}{8} \qquad (7)$$

B. *Floating body and pneumatic pump*

The floating body of the proposed device has upward and downward motions. The floating body moves upward when the incident wave amplitude increases from lowest point to the highest amplitude point. In the same way, the floating body moves downward when the amplitude reduces from maximum to minimum. This wave to floating body interaction can be drawn as a simplified circuit as in below [11 Fig. 2].

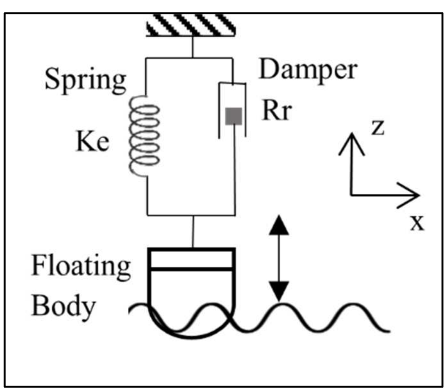

Figure 4- Schematic representing the floating buoy and OWC-Pneumatic pump interaction model.

Floating body movement can be written by following equation [10]:

$$M\frac{d^2z(t)}{dt^2} + R_r\frac{dz}{dt} + K_e z(t) = F_{wave} + F_{pump} \qquad (8)$$

where M is mass of the floating body, R_r is radiation coefficient and K_e is the elastic coefficient of the floating body. F_{wave} is the excitation force exerted on the floating body by sea wave and F_{pump} is the force exerted by the pump on the floating body.

The excitation force applied by sea waves to this oscillating floating body is given by [12]:

$$F_{wave} = \left[\frac{2pg^2A^2R_r}{\omega k}\right]^{1/2}\cos(\omega t) \qquad (9)$$

Force exerted by the pump with cross section area of A and pneumatic pressure P can be written as [10]:

$$F_{pump} = \begin{cases} A*P, & \frac{dz}{dt} \geq 0 \\ 0\;, & \frac{dz}{dt} < 0 \end{cases}$$

C. *Compressed air energy storage system*

The process of pumping and storing air at high pressure by the proposed device is illustrated in the figure below. The floating buoy moves upward and pumps the high-pressure air into the storage tank when an incident wave gives the excitation force upward to the floating buoy. Then the floating buoy comes down due to the gravitational force when the amplitude of the wave reduces. In this stage air enters the cylinder from the atmosphere. This thermodynamic process can be considered a polytropic process. Polytropic air compression is done with minimum work [13].

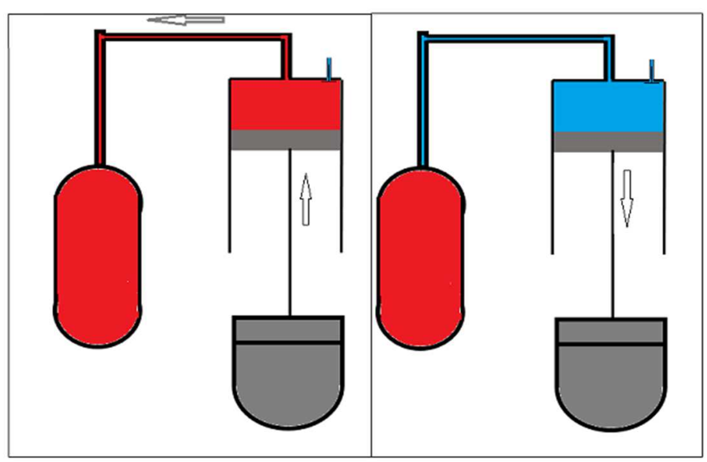

Figure 5-Schematic representation of the pneumatic pump and compressed air storage tank.

Since it is assumed as ideal gas and a polytropic air compression process, the work required to produced compressed gas can be given as [13]:

$$W = \frac{\gamma}{\gamma - 1} * P_1 V_1 \left(\left[\frac{P_2}{P_1}\right]^{\frac{\gamma}{\gamma-1}} - 1 \right)$$

where $\gamma = C_P / C_V$ is specific heat ratio, P_2 final pressure after compression and P_1 initial pressure of the air.

The wave to compressed air conversion efficiency can be given as:

$$\eta = \frac{W}{E_{Wave}} = \frac{8 * \frac{\gamma}{\gamma - 1} * P_1 V_1 \left(\left[\frac{P_2}{P_1}\right]^{\frac{\gamma}{\gamma-1}} - 1 \right)}{pgH^2} \eta_{con.}$$

here $\eta_{con.}$ is the conversion efficiency of the device.

Compressed air to electrical energy conversion efficiency can be expressed by:

$$\eta_{elect} = \frac{VI}{W_{gas}} = \frac{VI}{\frac{\gamma}{\gamma - 1} * P_1 V_1 \left(\left[\frac{P_2}{P_1}\right]^{\frac{\gamma}{\gamma-1}} - 1 \right)}$$

where W_{gas} is the energy released by the gas and V, I are the voltage and current output of the device.

IV. SIMULATION, EXPERIMENTS AND RESULTS

A. Simulation and results

The following figure 5 shows the relationship between wave height and the available wave energy. This analysis was done to estimate the available wave energy for different heights of sea waves. The total wave energy increases with the height of the wave.

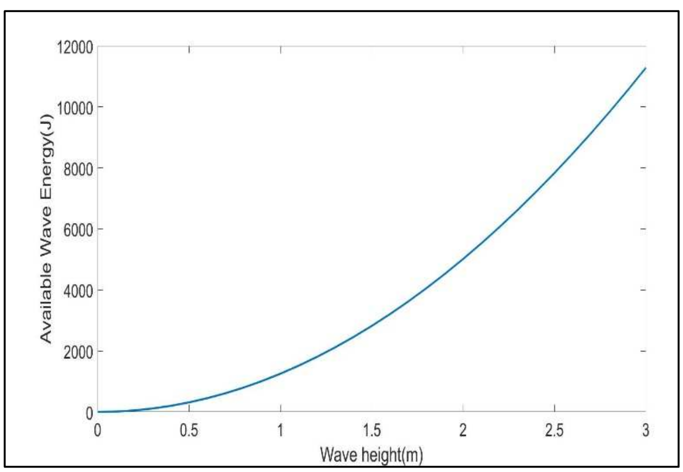

Figure 6-Available wave energy for different heights of sea waves

Figure 6 shows the required energy to store compressed air at different pressures. Assuming that $\gamma - 1.3$, volume of the tank is 20 l ($0.02m^3$) and the conversion efficiency of 0.7.

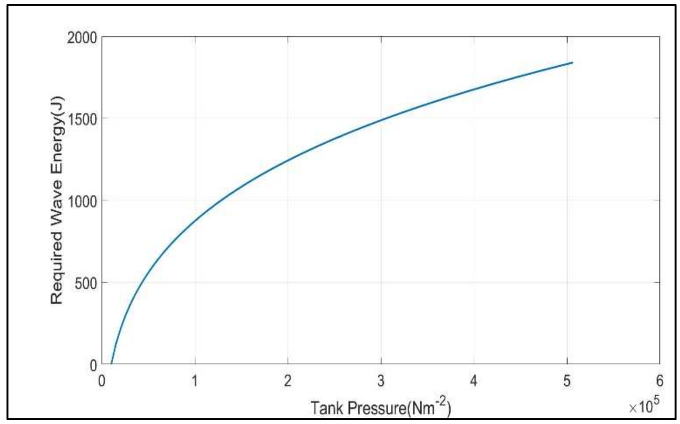

Figure 7- Required Wave Energy to store air in the storage tank at different pressure levels.

B. Experiments and results

A lab scale system, as in figure 8, was set up to evaluate the storage tank pressure and output power characteristics. As illustrated in figure 8, an external air compressor was used to pump the air at high pressure to the storage tank. Then, this high-pressure air is used to rotate an air turbine. The turbine was connected to a DC generator. Rated parameters of the generator are rated output voltage 24 V, rated speed 1500 rpm and maximum power 36 W.

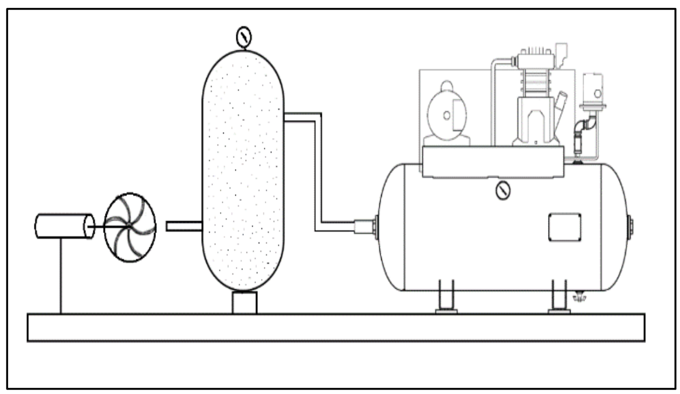

Figure 8- Schematic diagram showing the experimental set up.

The output power for different levels of air pressure is one of the important characteristics in analyzing the proposed wave energy converter. The tank pressure is relative to the atmospheric pressure and the initial pressure was kept as 0 and gradually increased up to 3.4 bar. The maximum pressure of the tank is kept at 3.4 bar due to the safety limit of the designed storage tank. Figure 9(a) shows the output power versus storage tank pressure characteristics curve obtained from experimental results. Figure 9(b) shows the difference between the output power versus storage tank pressure characteristics curve obtained from experimental results, and theoretical results.

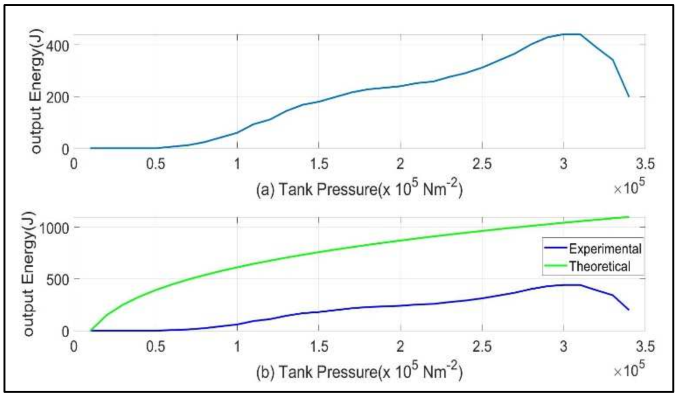

Figure 9-(a) experimental results showing the output energy vs tank pressure. (b) comparison of experimental and theoretical output energy plots.

Theoretically, the output power should increase with the air pressure. However, in the experiment the output power increases when the storage tank pressure is increased up to 3.1 bar. Then the output power reduces when the pressure increases further up to 3.4 bar. This could be mainly due to the constraints of the air turbine used for this experiment. When the air flow rate was high the rotational speed of the turbine got reduced. Output power remained zero up to 0.8 bar because the torque produced by the airflow was not enough to rotate the turbine. Optimal output occurs between 2.8 bar and 3.1 bar and the efficiency at this point is 42.36%.

Produced electrical energy from this device is small. However, this can be significantly improved by using higher conversion rate turbine and by increasing the size of the storage tank. Theoretical and simulation analysis is done for the proposed device. However, the experimental setup evaluates only the performance of energy storage concepts. Future work can be done to experimentally evaluate the performance of the power take off system of the device.

V. CONCLUSIONS

In this study a wave energy converter technology with compressed air energy storage system is discussed. Experimental and simulation analysis were done to obtain the characteristics of the proposed device. It was found that the compressed air to electrical energy conversion of the proposed device to be 42.3%. However, this can be significantly improved by using higher conversion rate turbines and by increasing the size of the storage tank. The proposed device with the energy storage system presents a realistic option for the development of DEEC-Tec structure.

REFERENCES

[1] "How wave energy could go big by getting smaller," NREL.gov, Jun-2017.[Online].Available: ttps://www.nrel.gov/news/program/2021/how-wave-energy-could-go-big-by-getting-smaller.html. [Accessed: 26-Dec-2022].

[2] J. Burhanudin, A. S. A. Hasim, A. M. Ishak, J. Burhanudin and S. M. F. B. S. M. Dardin, "A Review of Power Electronics for Nearshore Wave Energy Converter Applications," in IEEE Access, vol. 10, pp. 16670-16680, 2022, doi: 10.1109/ACCESS.2022.3148319.

[3] T. Kovaltchouk, A. Blavette, H. Ben Ahmed, B. Multon and J. Aubry, "Comparison between centralized and decentralized storage energy management for Direct Wave Energy Converter Farm," 2015 Tenth International Conference on Ecological Vehicles and Renewable Energies (EVER), 2015, pp. 1-8, doi: 10.1109/EVER.2015.7112985.

[4] F. Sharkey, J. MacEnri, E. Bannon, M. Conlon, and K. Gaughan, "Resource-induced voltage flicker for wave energy converters Assessment tools," IET Renew. Power Gen., vol. 7, no. 6, pp. 623–630, Nov. 2013.

[5] A. Blavette, D. L. O'Sullivan, R. Alcorn, T. W. Lewis, and M. G. Egan, "Impact of a medium-size wave farm on grids of different strength levels," IEEE Trans. Power Syst., vol. 29, no. 2, pp. 917–923, Mar. 2014.

[6] G. Rajapakse, S. Jayasinghe and A. Fleming, "Power Management of an Oscillating Water Column Wave Energy Converter with Battery/Supercapacitor Hybrid Energy Storage," 2018 8th International Conference on Power and Energy Systems (ICPES), 2018, pp. 246-251, doi: 10.1109/ICPESYS.2018.8626942.

[7] G. Rajapakse, A. Fleming, S. G. Jayasinghe, and M. Negnevitsky, "A Model Predictive Control-Based Power Converter System for Oscillating Water Column Wave Energy Converters," Energies Special Issue "Marine Energy", Feature Paper vol. 10, no. 10, 17/10 2017.

[8] G. Rajapakse, S. G. Jayasinghe, A. Fleming, and M. Negnevitsky, "Model Predictive Control for Electrical Power Converters of a Grid Integrated Oscillating Water Column with Energy Storage," Energies Special Issue "wave and Tidal Energy", vol. 11, no. 7, 2018.

[9] N. Tom, Review of Wave Energy Converter Power Take-Off Systems, Testing Practices, and Evaluation Metrics: Preprint, National Renewable Energy Laboratory, Golden, Co, rep., 2022.

[10] R. G. Dean and R. A. Dalrymple, *Water wave mechanics for engineers and scientists*, vol. 2. Singapore: World Scientific, 2009.

[11] I. R. Machado, E. H. Watanabe and P. B. Garcia-Rosa, "Modeling and analysis of a sea wave energy converter," 2015 IEEE 13th Brazilian Power Electronics Conference and 1st Southern Power Electronics Conference (COBEP/SPEC), 2015, pp. 1-7, doi: 10.1109/COBEP.2015.7420276.

[12] FALNES, J. (2002), "Ocean Waves and Oscillanting Systems Linear Interaction Including Wave-Energy, Cambridge University Press, USA

[13] V. Vongmanee, "The renewable energy applications for uninterruptible power supply based on compressed air energy storage system," 2009 IEEE Symposium on Industrial Electronics & Applications, 2009, pp. 827-830, doi: 10.1109/ISIEA.2009.5356337.