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Improvements in Distributed Compressed Air Energy Storage Efficiency through Turbine Multi-operating Point Optimization

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***Abstract*—Distributed compressed air energy storage (D-CAES) cycle is attractive –environmentally friendly energy storage option in small scale for stand-alone power generation using renewable energy sources. This work aims to enhance the overall performance of D-CAES through turbine multi-operating point optimization. The dynamic modelling for the cycle was carried out using Matlab/Simulink for both charging and discharging phases in order to identify small turbine operating map. In D-CAES operation, there is a significant variation in air thermodynamic properties and as a result the turbine was optimized for a range of operating condition by using CFD modelling and genetic algorithm optimization to achieve higher efficiency levels during discharging phase. The multi-operating point turbine optimization approach could improve the D-CAES cycle overall efficiency by 8.69%.**

***Keywords*— D-CAES- Dynamic Modelling- CFD- Optimization-Genetic Algorithm**

I. INTRODUCTION

In recent years, the use of renewable energy sources for electricity generation has grown rapidly over the world. Although the technology of using renewable energy has matured, it is still unable to meet electricity consumer’s demand due to significant variations in weather conditions over time which make renewable sources uncontrollable and unpredictable energy supplier. To enable more development of using renewable resources for sustainable power production there is a great need to implement energy storage technology to maintain electricity supply and facilitate the use of renewable energy sources for different applications. The common massive energy storage technologies include: batteries, pumped hydro, flywheels, and compressed air energy storage [1-3].

Compressed air energy storage (CAES) is a valuable promising storage technology for cost effective environmentally friendly electricity generation with high storage capacity. Large CAES is a proven technology and its history back to the first power plant in 1978 Huntorf, Germany with large underground cavern with an output power of 290MW for four hours. The second CAES plant is McIntosh Alabama in USA which could produce 110MW for 26 hours [4-6]. In large conventional CAES, the air entering the turbine is heated by the combustion of gases which increase the fuel consumption and CO2 emissions. Also, there is a significant loss in heat during compression stage which affects the cycle efficiency. Furthermore, the development of conventional CAES based on renewable energy has limitations due to complex geological characteristics of large underground caverns [7, 8].

The new focus on developing CAES aims to improve the cycle overall efficiency through several alternative CAES configurations which have been proposed as innovative cycles for higher performance. These developed CAES cycles include: Advanced Adiabatic CAES (A-A-CAES) which aims to store the lost heat during compression stage by applying thermal energy storage (TES); Isothermal CAES which aims to prevent any heat exchange externally in order to achieve closely isothermal compression using atomized water injection; and small CAES or distributed compressed air energy storage (D-CAES)[9-12].

Small and medium distributed stand-alone power generation at consumption point can be achieved using small high pressure air receiver for cost effective and clean operation. In small CAES the air can be compressed in man-made pressurized vessels up to 300 bars for distributed power cycle with an overall efficiency up to 50% [1].

Small CAES offers many advantages which include: long cycle time, safe technology, environmental friendly, high storage capacity compared with batteries, can be ingenerated with renewable energy sources for cost effective electricity supply, less installation restrictions, appropriate for distributed power generation, long

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expander operating life time, non-toxic, and simple manufacturing [11]. However, this technology is not proven yet and further research is required to improve cycle efficiency. Furthermore, the discharge pressure varies and the expansion device works deeply in off-design operating conditions which lead to significant loss in turbine efficiency and overall cycle performance [2].

A detailed analysis of mini scale CAES cycle was carried out by Khamis et al (2011) for a system with pressure vessel of 270L at 11 bars for electricity generation based on micro turbine with 800RPM. The system could only obtain 8 VAC and the design goal was 12 VAC and this gap is due to the drop in pressure and temperature entering to micro turbine. Also increasing inlet turbine pressure reduces the tank discharge time [13].

Villela et al (2010) proposed small scale compressed air storage system for power generation in residential unit. The main focus on this study was to develop small CAES system integrated with solar PV panel as energy source and fluid piston as expansion device. This work found that the system performance is correlated with compressor RPM and the efficiency of piston expansion device [14].

The implementation of the technology of thermal energy storage (TES) in D-CAES is one of key research areas in developing CAES for more efficient power production. There is a novel proposed CAES integrated with TES introduced by Jannelli et al 2014. In this work, a numerical methodology for D-CAES power plant sizing was presented. The implementation of TES with intercooling compression and inter heating expansion could save 17% of the required cooling. However, in this proposed cycle configuration the PV unit was oversize to meet the energy daily consumption[15].

The feasibility study on small CAES for portable electrical and electronic devices application based on micro turbine was introduced by Paloheimo et al. (2009). This study concluded that the power and efficiency of small CAES unit depend on turbine efficiency and further developments in turbine design are required for such applications [16].

It is obvious from the review that the D-CAES cycle performance is correlated with turbine efficiency which is characterized by operating conditions. Due the variations in CAES discharging pressure (turbine inlet pressure) and mass flow rate, the turbine works in off design mode. In this paper, theoretical investigation on 1kW distributed CAES driven by solar PV model with an implementation of TES was presented. Multi operating point turbine optimization was carried out based on CFD modelling and GA optimization to maximize turbine efficiency in order to identify an efficient novel blade design for multi operating conditions.

II. D-CAES CYCLE CONFIGURATION

In this study, small distributed (D-CAES) based on solar PV as energy source is proposed. The CAES cycle is implemented with TES for storing lost thermal energy during compression phase. Fig.1 shows the proposed cycle configuration which consists of:

- Solar PV as a motor or generator that provide the energy source for air compressor operation.
- Air compressor which is required for air compression in small pressure vessel.
- Small CAES which is high pressure cylinder to store the energy in a form of compressed air.
- Micro turbine in which the energy can be extracted via air expansion.

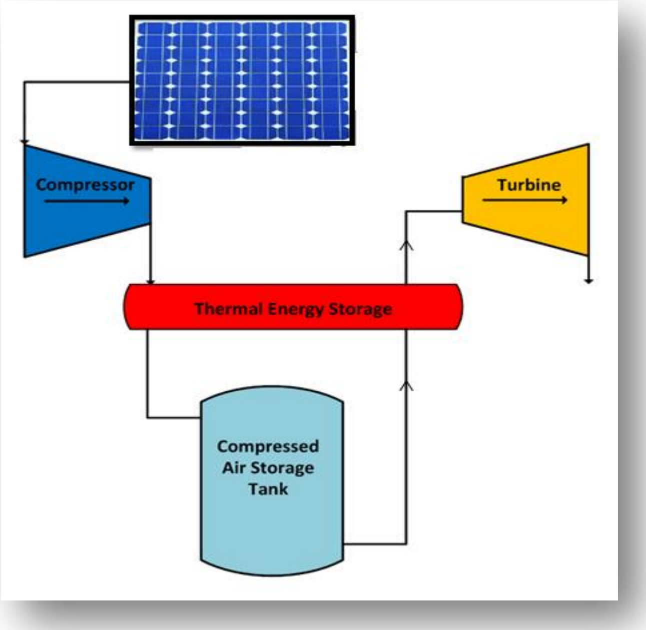

Fig.1 Proposed D-CAES Cycle Configuration

As can be seen the solar PV can be used to run the compressor to store the energy in a form of compressed air and the stored energy can be recovered to generate electricity by air expansion through micro turbine. The air entering the turbine can be heated up using TES. The overall performance of this cycle depends on the thermodynamic performance of CAES for both charging and discharging phases. During the expansion phase, the cycle overall performance is correlated with micro turbine efficiency.

III. D-CAES DYNAMIC MODELLING

The CAES system can be described as unsteady open system due to the significant variations in air temperature, pressure and mass for both charging and discharging processes [17]. For the proposed small D-CAES, the cycle was modelled in Matlab/Simulink in order to define dynamic properties of the system and to identify turbine operating conditions. The Matlab/Simulink offers the advantage of using integrators to determine the instantaneous air properties (pressure, temperature and mass) for different cycle components as shown in Fig. 2.

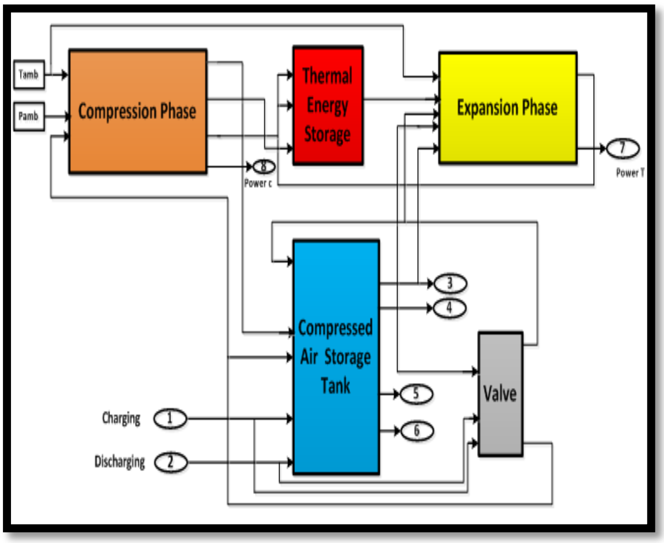

Fig. 2 Matlab Simulink Blocks for CAES Cycle

A. *Compression phase:*

In compression phase, the atmospheric air is compressed with the compressor train for desired pressure ratio and mass flow rate. The outlet pressure and temperature of the air leaving the compressor can be calculated according to:

$$p_{c,out} = p_{amb} * \pi_c \tag{1}$$

$$T_{c,out} = T_{amb} * (\pi_c)^{\frac{n_c-1}{n_c}} \tag{2}$$

Where:

$p_{c,out}, T_{c,out}$ are the outlet pressure and temperature.

p_{amb}, T_{amb} are the atmospheric pressure and temperature.

π_c is the compressor pressure ratio.

n_c is the polytropic index for the compressor.

The compressor power can be calculated as:

$$P_c = \frac{1}{\eta_c}\dot{m}_{c,a} C_P T_{amb}\left[\pi_c^{\frac{n_c-1}{n_c}} - 1\right] \tag{3}$$

B. *THERMAL ENERGY STORAGE(TES):*

Thermal energy storage is the technology that can store thermal energy at certain temperature by changing material internal energy. This can be can be achieved through sensible heat storage (SHS), latent heat storage (LHS), and bond heat storage (BHS) [18, 19]. To restore the thermal energy dissipated during compression phase and to reheat the air entering the turbine, TES was implemented in the cycle to produce adiabatic system. For solar power plant heat storage, solid media sensible heat storage is attractive thermal energy storage technology due to simplicity, and cost. The concrete as a sensible heat storage was developed by German Aerospace Centre for solar power application. The ability of concrete as a favourable storage media was proven and could store thermal energy up to temperature of 400^{o}c [20]. In this study, the concrete is used as sensible heat storage for the D-CAES cycle as shown in Fig.3 and the heat balance in the TES can be expressed as following:

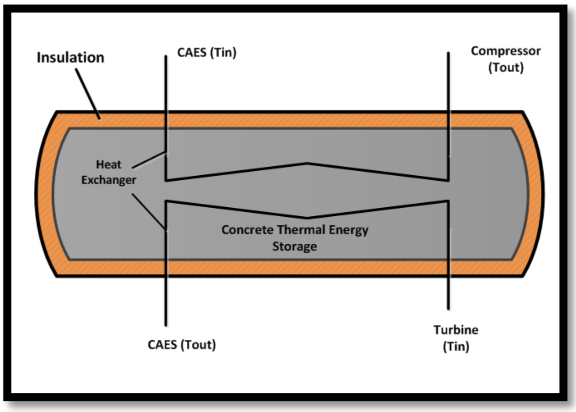

Fig. 3 TES system with heat exchanger

$$m_{TES} C_{P(TES)} \frac{dT_{TES}}{dt} = \dot{q}_{compression} - \dot{q}_{expansion} - \dot{q}_{loss} \tag{4}$$

Where the ρ_{TES} is the density of TES (2750kg/m3), $C_{P(TES)}$ is the specific heat of TES (916J/Kg.K), $\dot{q}_{compression}$ is the heat generated during compression, $\dot{q}_{expansion}$ is the heat required to reheat the air entering the turbine during expansion stage, and $\dot{q}_{loss}$ Is the heat lost to the surrounding.

C. *AIR STORAGE TANK:*

For the storage tank and by assuming the tank is adiabatic with constant volume, both the charging and discharging phases can be described using ideal gas equation as:

$$\frac{dp}{dt} = \frac{d}{dt}\left(\frac{mRT}{V}\right) = \frac{R}{V}\frac{d}{dt}(mT) \tag{5}$$

For the ideal gas:

$$\frac{T^{\frac{\gamma-1}{\gamma}}}{p} = constant \tag{6}$$

Equation (6) can be written in a form of derivation terms as:

$$\frac{dT}{dt} = \frac{T}{p}\left[1 - \frac{1}{\gamma}\right]\left[\frac{dp}{dt}\right] \tag{7}$$

Using equations (5) and (7) the rate of temperature change can be determined as:

$$\left[\frac{dT}{dt}\right]_{tank} = \frac{1}{m_{a_{tank}}}\left(1 - \frac{1}{\gamma}\right)\left[\dot{m}_{air}^{in} T_{air}^{in} - \dot{m}_{air}^{out} T_{air}^{out}\right] \tag{10}$$

Where $m_{a_{tank}}$ is the instantaneous air mas in the tank which can be expressed as:

$$m_{a_{tank}} = \int_0^t [\dot{m}_{in} - \dot{m}_{out}]\, dt \tag{11}$$

D. *EXPANSION PHASE:*

In this phase, the compressed air is expanded through a small turbine to extract the sored energy. The air entering the turbine is withdrawn from the storage tank at nearly ambient temperature and passed through TES for increasing turbine inlet temperature. The output power of the turbine can be determined as:

$$P_t = \eta_t \dot{m}_t C_{P_a} T_{t,air}^{in}\left[1 - (\pi_t)^{\frac{n_t-1}{n_t}}\right] \tag{12}$$

Where $\dot{m}_t$ is discharge mass flow rate and $T_{t,air}^{in}$ is the temperature of the air leaving TES and entering the turbine.

Using the previous thermodynamic correlations, the D-CAES system was modelled using Math lab Simulink to identify the operating map and design specifications of the small turbine. To increase the potential of D-CAES for energy production applications, the discharge phase (expansion process) needs to be improved for higher system overall efficiency [21]. From turbine design point of view, the turbine is designed for unique identified operating point for certain output. However, in actual turbine operation, there is a high possibility that the turbine will be operated for a range of operating conditions leads to variations in turbine performance levels [22].

The primary aspect to increase the system performance is improving the turbine efficiency in off design operating modes. In D-CAES, the turbine works deeply in off design conditions as a result of inlet air properties variations. The inlet pressure can be controlled using pressure regulating valve. However, the controlled discharging pressure leads to change in mass flow rate and cycle performance as[23, 24]:

$$\dot{m}_{actual} = \dot{m}_{ref} . \frac{p}{p_{ref}}\sqrt{\frac{T_{ref}}{T}} \tag{13}$$

$$\eta_{actual} = \eta_{ref}\left[1 - \left(\sqrt{\frac{\Delta h_{ref}}{\Delta h}} - 1\right)^2\right] \tag{14}$$

TABLE I

Simulink Model Parameters:

Parameter	Unit	Value
Ambient temperature	k	290
Ambient Pressure	bar	1
Compressor flow rate	Kg/sec	0.2
Compressor efficiency	[-]	0.86
Turbine mass flow rate	Kg/sec	0.1
Max tank Pressure	bar	10-20
Air Tank volume	litter	1000

IV. TURBINE MULTI-POINT OPTIMIZATION

The turbine design optimization is normally conducted by redesigning blade profile for a certain operating condition (design point) and this approach is known as single point optimization. However, in D-CAES expansion phase, the turbine is run for a wide range of operating conditions leading to that the turbine works deeply in off design conditions for long time.

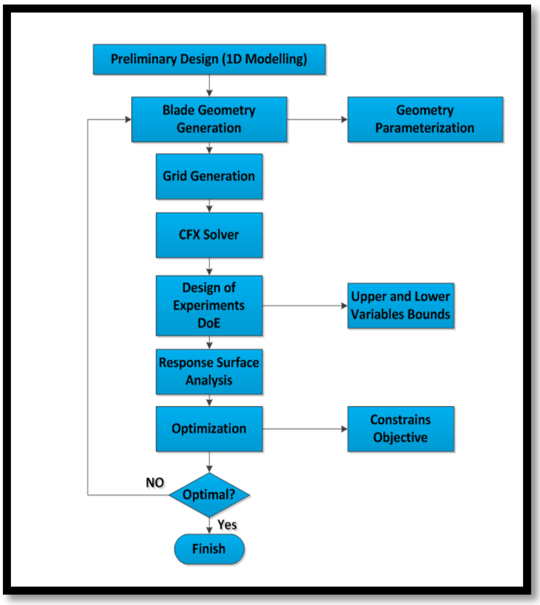

Fig. 4 Turbine Optimization Strategy

A multi-point optimization is an optimization approach which is performed for a range of operating conditions to ensure that turbine has acceptable performance levels at this operation range. This can be achieved by using genetic algorithms (GA), design points database generated by design of experiment (DoE) approach [25]. The multi-point optimization approach aims to stabilize turbine mass flow rate (avoiding stall region) which can be achieved by blade curvature variations to predict turbine performance for different inlet conditions [26]. Fig.4 shows the optimization strategy using ANSYS CFX 15.

V. RESULTS:

The thermodynamic analysis of CAES for both charging and discharging using thermodynamic relations was conducted. This analysis can define the energy required for storage tank charging as well as the amount of the energy that can be stored in the system. The energy required for charging stage was calculated for two tanks 200L, 400L, and 1000L as shown in Fig.5 The amount of tank charging energy is dependent upon the charging entire pressure.

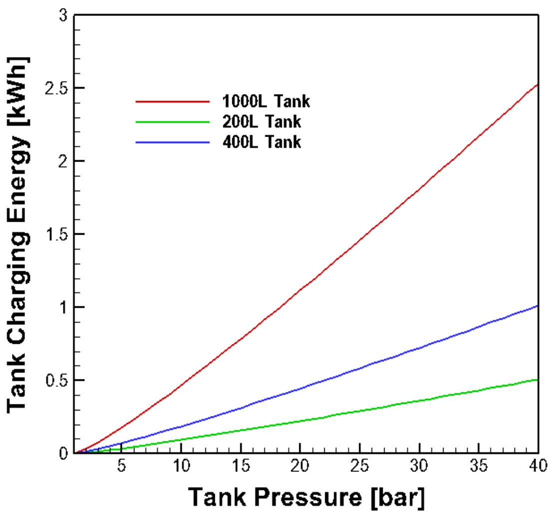

Fig. 5 Energy Required for Charging CAES Tank

The stored energy in the system is shown in Fig 6 and 7 in terms of energy density [Whrs/Lit] and specific energy [kj/kg] for both adiabatic and isothermal calculations. As can be seen the calculated energy by isothermal equations is higher than adiabatic due to the assumption that the temperature of the air remains constant which actually cannot be achieved. The stored energy is calculated for a range of entire tank pressure (100-5000kpa) and the maximum stored energy was (4.874 Whrs/Lit) in isothermal charging and (2.109 Whrs/Lit) in adiabatic process.

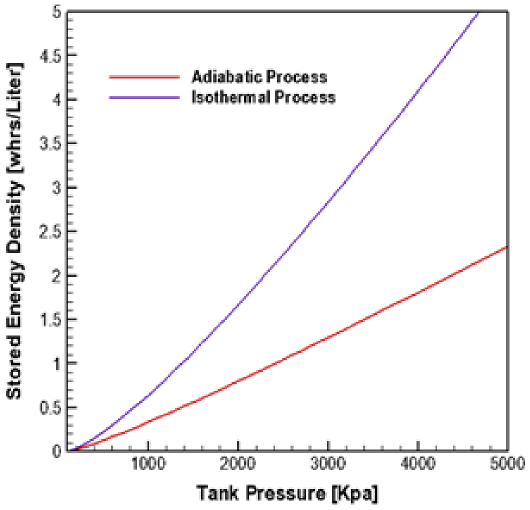

Fig. 6 Energy Density for different Pressure

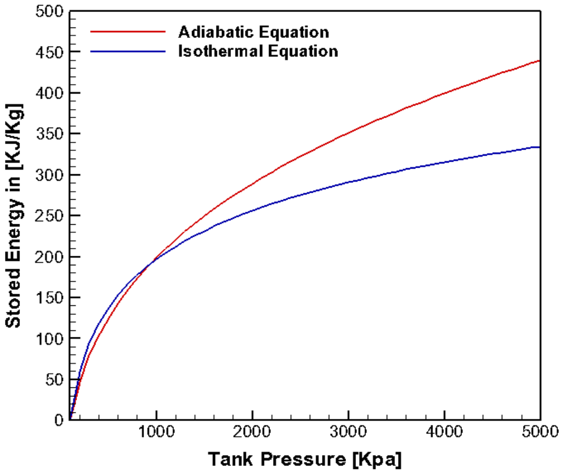

Fig. 7 Specific Energy for different Pressure

The discharging air pressure of tank is a key parameter in evaluating the performance of distributed CAES cycle as well as the cycle operation time. Fig.8 and Fig.9 show the variations in tank pressure for controlled and uncontrolled discharging pressure for different maximum tank pressures. These curves represent the micro turbine operating map and cycle operation time estimation. The tank discharge time can be increased as shown in figure 13 by discharging tank at controlled pressure. As a result the cycle operation time can be increased by (560seconds) and this controlled pressure also can provide stable inlet conditions for micro turbine.

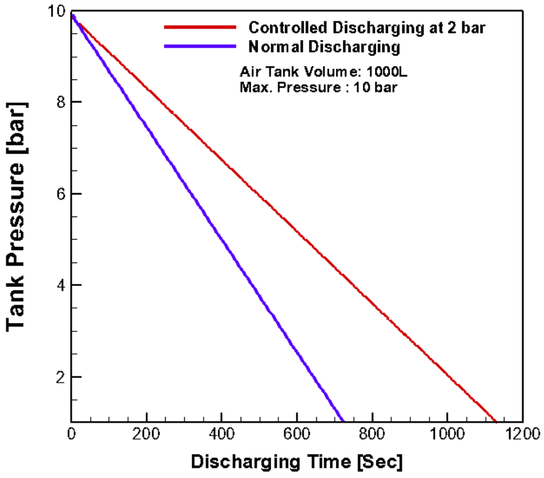

Fig. 8 Air Tank Discharging for max. Tank Pressure 10 bar

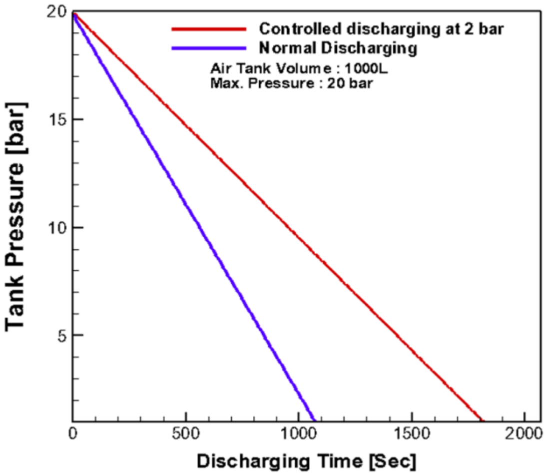

Fig. 9 Air Tank Discharging for max. Tank Pressure 20 bar

As shown in Fig.10 there is a reduction in mass flow rate which leads to that the turbine will work deeply in off design mode and this leads to decrease the performance levels like output power which is effected significantly by mass flow rate variations as can be seen in Fig.11.

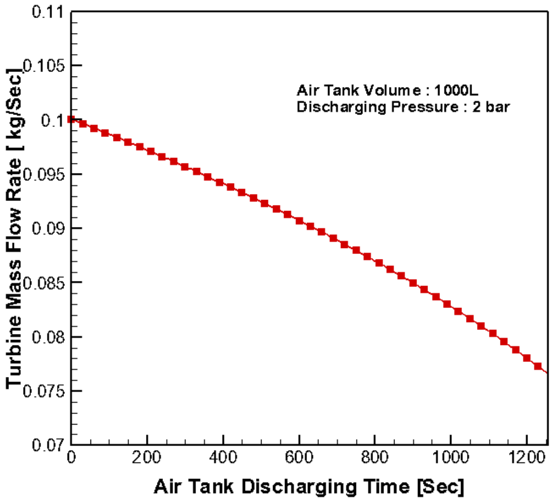

Fig. 10 Turbine inlet mass flow rate variations

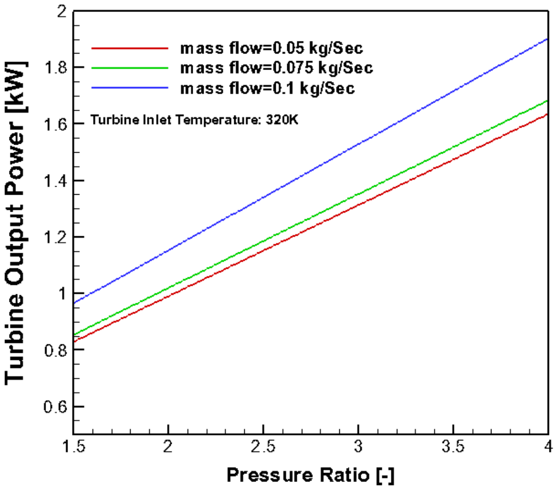

Fig. 11 Turbine output power for different mass flow rate

For the proposed D-CAES axial turbine is selected as it can be operated at low inlet pressure with high efficiency levels compared with radial with required inlet pressure of 4-5 bars and with rotational speed greater than 65,000 RPM to achieve higher efficiency[27]. As a result of variations in mass flow rate, the axial turbine multi-operating point optimization was performed using ANSYS CFX 15 and GA approach for turbine profile optimization in off-design operation modes. Fig.12 shows a comparison between optimized and un-optimized rotor blade profiles for different inlet mass flow rate [0.07-0.1kg/sec] and as can be seen there is significant change in blade solidity compared with original design to handle different inlet mass flow rate values. The multi-operating point approach can improve the overall efficiency of D-CAES by 8.69% as shown in Fig.13.

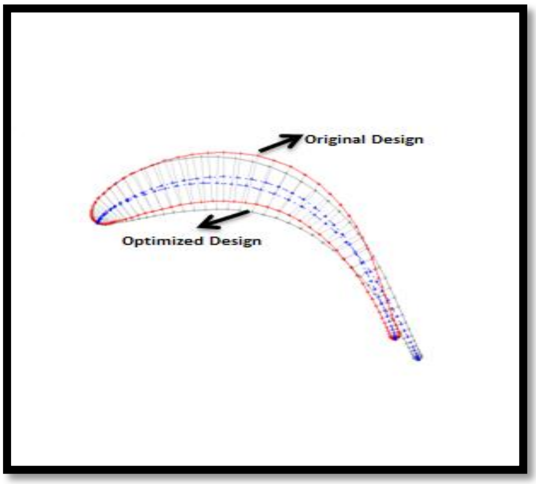

Fig. 12 Comparison between optimized and un-optimized turbine rotor profiles.

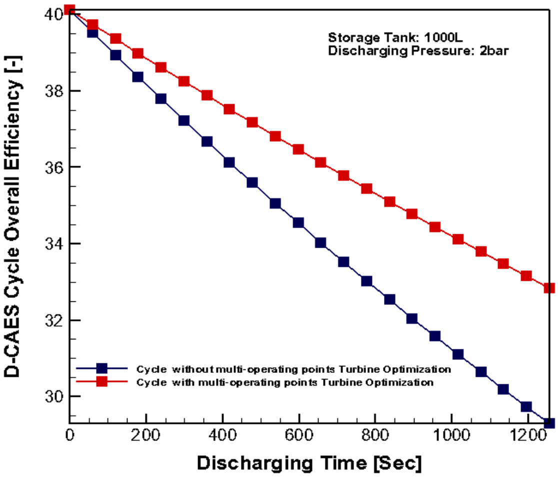

Fig. 13 Comparison between D-CAES overall Efficiency for both optimized and un-optimized turbine

VI. CONCLUSION

In this Work, The dynamic modelling of Distributed compressed air energy storage (D-CAES) cycle was conducted using Matlab/Simulink in order to define the design parameters of turbine expander. This work aims to improve the overall performance of D-CAES through turbine multi-operating point optimization. In D-CAES operation, there is a significant variation in air thermodynamic properties which leads to considerable turbine loss and as a result the turbine design was optimized for a range of operating condition using ANSYS CFX modelling and genetic algorithm optimization to achieve higher efficiency levels during expansion process. The multi-point optimization approach could improve the D-CAES efficiency by 8.69%.

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