Optimized Mini Notched Turbine Energy Harvesting Using Resistor Emulation Approach and Particle Swarm Optimization

Majdi M. Ababneh, Samuel Perez, and Sylvia Thomas

Department of Electrical Engineering
University of South Florida
Tampa, Fl, United States
Email: {mababneh, sperez2}@mail.usf.edu, Sylvia@usf.edu

Abstract— **This paper proposes a novel mini notched turbine that can be used as feasible energy source and a methodology for optimizing maximum power point tracking system to improve the efficiency of DC-DC converter and then improve the total efficiency of energy harvesting systems, this is accomplished using particle swarm optimization technique, where the converter efficiency is used as the fitness function and inductor and on-time were chosen as optimized parameters. This design improves the DC-DC converter efficiency and the efficiency of maximum power tracking system by 9.25% comparing with conventional maximum power tracking systems over a wide range of input power and optimal load resistances, allowing harvesting more power and delivering it to load. The purpose of this approach is not limited to ultra low power applications; it can easily be extended in portable applications to extend the battery life.**

Keywords— **Notched Turbine, DC-DC Converter, Maximum Power Point Tracking (MPPT), Resistor Emulation, Particle Swarm Optimization (PSO), Modeling and Optimization, and Low Power Applications.**

I. INTRODUCTION

The need for ultra low power for standalone embedded systems that need to operate for very long time devices is growing rapidly. The requirements in this market for low power, long life, push the limits of current technologies and existing solutions that maybe applicable to low power applications. Therefore, new techniques and creative designs are required to meet the urgent requirements of today's cutting edge low power devices.

The development of technologies that allow miniature low power wireless devices is essential because of their huge effect on the extended battery life. One approach is to get energy using maximum power point tracking system for extended battery life. Getting maximum output power from the source using maximum power point tracking is a primary challenge because the amount of the energy provided by low power sources like photovoltaic and wind power systems is often very low (~ 10-100µW) and high power consumption of components that used in energy harvesting system. Therefore, the lifetime of low power applications is still limited. Modern Turbine systems are increasingly required to satisfy the needs of ultra low power devices [1], but the most important goal is improving environmental compatibility and adaptability without detriment to their performance. There are limitations in the use of micro turbines when the application demands specials characteristics such as input and output size and shape, and adaptability to be used in different positions [2], [3]. Traditional impulse turbines, such as pelton and Banki [3]-[5], have a fixed orientation and position, and do not require pressure around the rotor chamber.

This paper presents a novel mini notched turbine that can be used as feasible energy source to meet energy needs of low power applications with an overall volume below 15cm^3 and an approach for gathering near maximum power by improving the efficiency of DC-DC converter from any variable low-power sources. Convenient MPPT techniques are not suitable for very low power sources due to high-power overhead of components that used in the system.

Based on that, particle swarm optimization (PSO) technique was successfully applied to select proper values of inductor and on-time to improve DC-DC converter efficiency where the converter efficiency is used as fitness function and inductor and the on-time were chosen as optimized parameters [6]-[9].

The paper is organized as follows: Section II describes mini notched turbine system and generated power. The principles of resistor emulation using boost converter are presented in Sections III. Optimized configuration of boost converter is presented in Section IV. Simulation results are discussed in Section V. Finally, Section VI concludes the paper.

II. NOVEL MINI NOTCHED TURBINE

The great innovations of the last century have ushered continuous progress in many areas of technology, especially in the form of miniaturization of electronic circuits. This progress shows a trend towards consistent increases in memory density, processing speed and power density; and towards a decrease in power requirements due to miniaturization [10]. A lot of power sources can be used in order to provide power to low power applications [11]. Most of them have potential characteristics and can be designed to deliver a maximum power like Mini notched turbine. It is a novel device that can be used for converting flow into electrical energy by using electromagnetic subsystems to transform kinetic energy into electricity. The mini notched turbine has increased efficiency over traditional turbine systems due to changes in the inclination angle of the nozzle and large hub diameter and blade attachment reducing vortices and increasing internal pressure as shown in Fig. 1 and Fig. 2, and because of that, the generated power of the mini notched turbine has been increased by 35% over traditional turbine systems under same conditions [12]-[14].

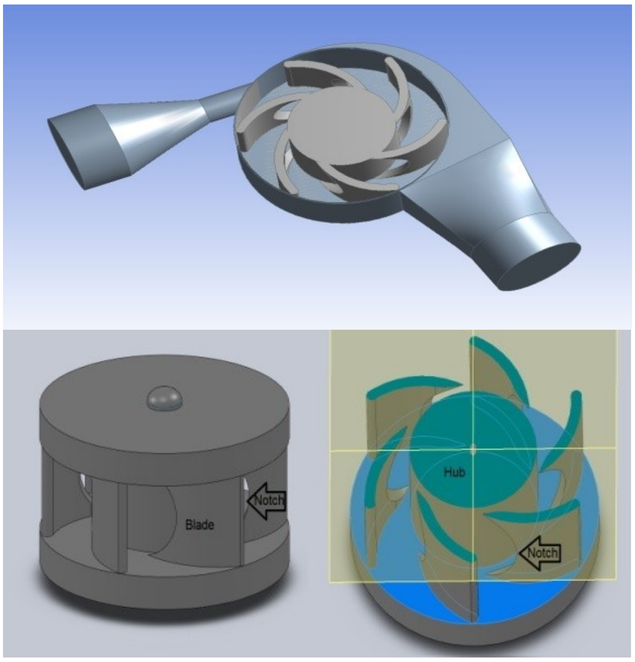

Fig. 1. Mini notched turbine design.

Fig. 2. Mini notched turbine approaches.

Mini notched turbine is being prototyped and tested on a miniaturized energy generator system (Patent in Progress), which could be used as a green energy source, that converts biomechanical energy from some kinds of microfluids to electrical energy. Fig. 3 shows generated power from mini notched turbine varies as a function of output voltage for different flow speeds and shows that, for any given flow speed, there is an optimal output voltage where the generated power is maximized, output voltage of mini notched turbine is in the range of 0-1V and maximum generated power is 38.8mW for 2250 RPM flow speed. Fig. 4 shows I-V characteristics of mini notched turbine which help us to locate and calculate load impedances that maximize generated power at different flow speeds, these impedances will be used later in the optimization in order to improve the total efficiency of power management circuit.

Based on Fig. 5, generated power measurements obtained experimentally from mini notched turbine over a range of generator speeds (500-2250 RPM) are measured with different values of resistance loadings. It is observed that the mini notched turbine can generate up to 38.8mW at high generator speed comparing with 27.4mW from non notched turbine which is 35% higher and it can generate up to 7.5 mW at average speed, these maximum values can be gathered under impedance matching condition.

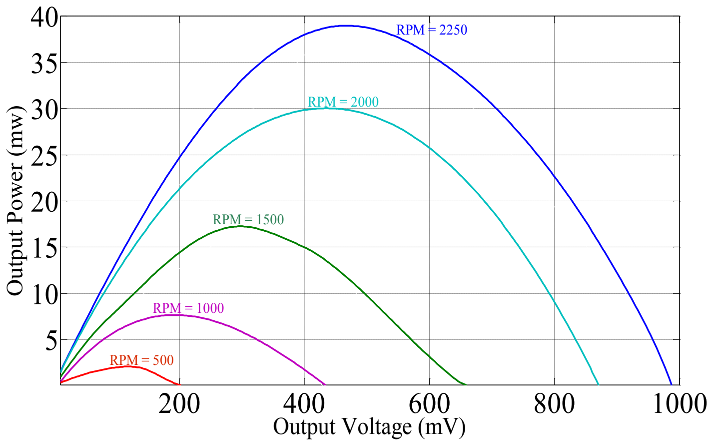

Fig. 3. Measured generated power against output voltage.

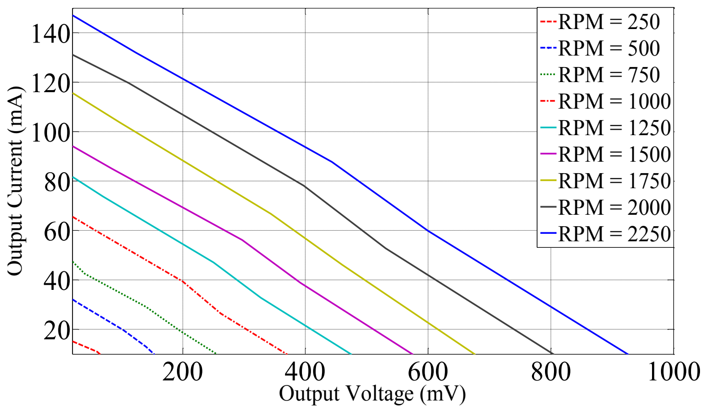

Fig. 4. Measured I-V Characteristics of mini notched turbine for different flow speeds.

Mini notched turbine differs from other turbine models in three main ways. First, the design makes it possible for the turbine to be immersed in a dynamic fluid, and be able to work in different positions and orientations. Second, the preferred embodiment of the turbine rotor utilizes a new blade curvature and shape, in addition to a semicircular notch on the internal proximal edge of each blade, to aid in the fluid redirection and allows a continuous circulation of fluid inside the rotor chamber. Third, the casing, coupled with the notched blades, optimizes the flow of the fluid injected at the inlet and prevents drastic alterations and changes in pressure of the working fluid through the turbine, thus maintaining volumetric pressure on the surface of the blades that are not directly impacted by the initial fluid stream.

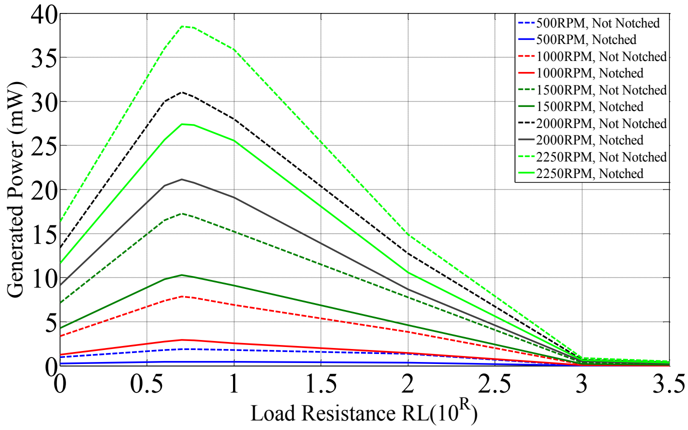

Fig. 5. Measured generated power against output voltage.

III. Principles Of Resistor Emulation Using Boost Converter

In the last decade, Resistor emulation technique has been used to find the maximum power point for low power applications, most commonly in photovoltaic and wind applications. The idea is based on using DC-DC converters with natural resistor emulation at the input to match impedances of energy source and the load. Boost, buck converters, and buck-boost converters in discontinuous conduction mode (DCM) can be used for resistor emulation where resistance depends on values of inductor and on time. If the boost converter is operated in DCM as shown in Fig. 6 below, then resistance emulation is [6], [7], [15]

$$R_{\mathrm{op}} = R_{\mathrm{em}} = \frac{2LT_{\mathrm{control}}}{t^2_{\mathrm{on}}\alpha}\left(\frac{M-1}{M}\right) \tag{1}$$

where L is inductance, t_{on} is on time of MOSFET, α is switching factor, and $M = {}^{V_{\mathrm{o}}}\!/_{V_{\mathrm{in}}}$.

At very low power incoming from source, input voltage of the converter is typically very low. Therefore, (1) can be simplified to [6]:

$$R_{\mathrm{op}} = R_{\mathrm{em}} = \frac{2LT_{\mathrm{control}}}{t^2_{\mathrm{on}}\alpha} \tag{2}$$

where $\left[\frac{M\text{-}1}{M}\right] \approx 1$. For simplicity, T_{control} assumed to be half of on time, then resistance emulation is [6]

$$R_{\mathrm{op}} = R_{\mathrm{em}} = \frac{4L}{t_{\mathrm{on}}\alpha} \tag{3}$$

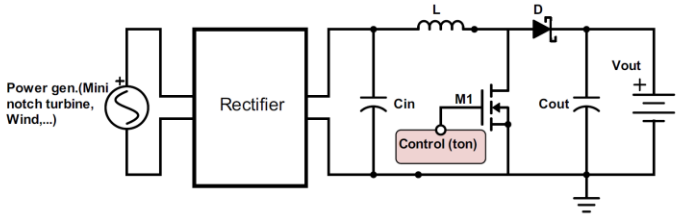

Fig. 6. Boost converter with control trigger for the MOSFET.

IV. Boost Converter Configuration With PSO Technique

Particle Swarm Optimization (PSO) finds the best possible solution according to a predefined fitness function for a nonlinear problem by moving interacting particles and choosing the best solutions by comparing the particle's best solution with the global best solution obtained by all particles [16]. This technique was proposed in 1995, based on analogy with biological swarming observed in insect swarms, bird flocks, and fish schools [17]. The flow chart of PSO algorithm is shown in Fig. 7. PSO technique is capable of achieving solid, accurate, and rapid solutions to several complex optimization problems. It is a stochastic, adaptive population-based optimization algorithm. It's a large number of searches using a group of particles, which is appropriate to solve large-scale optimization problems [18]-[20].

The main idea of PSO is finding the best result or at least acceptable result for a multi-dimensional optimization issue based on the movement of particles and interactions between them by comparing the best personal solution of each particle and the best global one using a known fitness function [16], [19]-[21]. The aim of applying PSO algorithm is to have best values of L and t_{on} that can output maximum converter efficiency. The selection of values of inductor and on time for boost converter depends on power losses, emulated resistance, input power, and output voltage. PSO technique is applied on a boost DC-DC converter design from [6].

A. Selection of L and t_{on}

PSO optimization technique is used to find the best value of L and t_{on} that can produce high converter efficiency by run simulation over expressions (4-10) where power loss includes switching loss, conduction loss, and control loss as shown below.

$$P_{\mathrm{loss}} = P_{\mathrm{in}} - P_{\mathrm{out}} = P_{\mathrm{control}} + P_{\mathrm{switching}} + P_{\mathrm{conduction}} \tag{4}$$

$$P_{\mathrm{conduction}} = \left(R_{\mathrm{L,ESR}} * I^2_{\mathrm{L,rms}} + R_{\mathrm{on}} * I^2_{\mathrm{L,rms1}} + P_{\mathrm{Diode}}\right) * \alpha, \tag{5}$$

$$P_{\mathrm{switching}} = \frac{\alpha}{2t_{\mathrm{on}}}\left(V_{\mathrm{o}}Q_{\mathrm{M1}} + V^2_{\mathrm{in}}\,\mathrm{C}_{\mathrm{oss\_1}}\right) \tag{6}$$

$$P_{\mathrm{control}} = P_{\mathrm{pwm}} * \alpha + P_{\mathrm{operating}} \tag{7}$$

$$P_{\mathrm{Diode}} = \frac{V^2_{\mathrm{in}}}{V_{\mathrm{o}} - V_{\mathrm{in}}}\frac{V_{\mathrm{D}} * t_{\mathrm{on}}}{4L} \tag{8}$$

$$R_{\mathrm{L,ESR}} = \left(8e12 * L^4\right)\left(1e10 * L^3\right) + \left(4e6 * L^2\right) + \left(3909 * L\right) \tag{9}$$

$$I_{\mathrm{L,rms}} = \frac{1}{\sqrt{6}} \frac{V_{\mathrm{in}} * t_{\mathrm{on}}}{L},$$
$$I_{\mathrm{L,rms1}} = I_{\mathrm{L,rms}} \sqrt{\frac{V_{\mathrm{in}}}{V_{\mathrm{o}} - V_{\mathrm{in}}}} \tag{10}$$

where $R_{\mathrm{L,ESR}}$ is equivalent series resistance of inductor, R_{on} is MOSFET resistance when it's on, Q_{M1} is gate charge, $C_{\mathrm{oss\_1}}$ is output capacitance of the MOSFET,

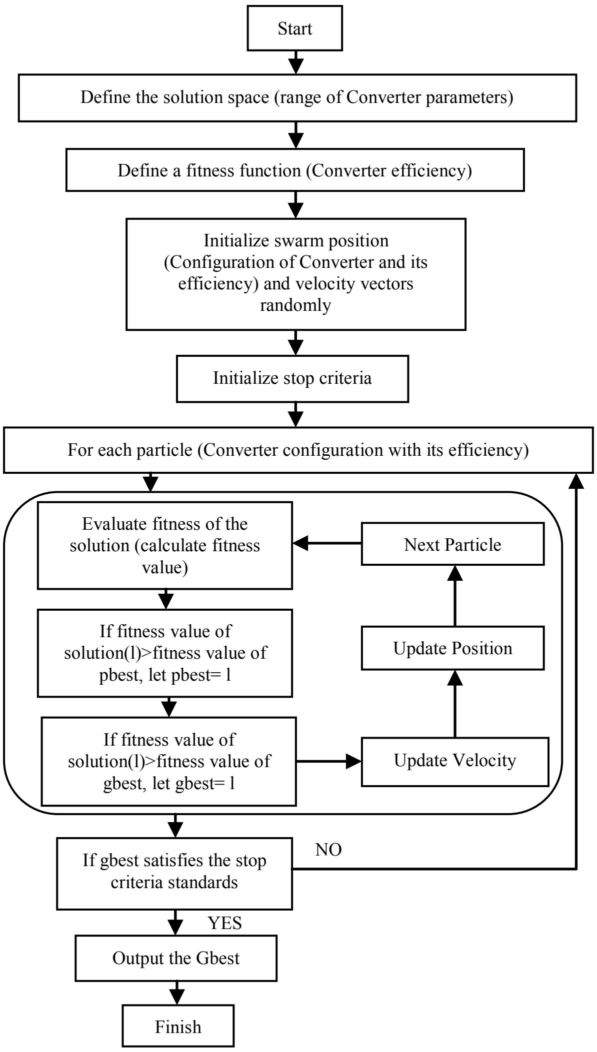

Fig. 7. Flow chart of PSO technique.

P_{pwm} is power loss of pulse width modulation , $P_{\mathrm{operating}}$ includes other losses of control circuitry .

B. Selection of PSO Parameters

Particle location is updated according to the following expressions [22], [23]:

$$l_i^t = l_i^{t-1} + v_i^t * \Delta t \tag{11}$$

where subscripts i refers to particle number, l_i^t is new particle position, l_i^{t-1} is previous position, and Δt is time step that velocity is applied for. Particle velocity is updated according to the following equation [23]:

$$v_i^t = w * v_i^{t-1} + c_1 * r_1^t * (p_i^t - l_i^{t-1}) + c_2 * r_2^t * (g^t - l_i^{t-1}) \tag{12}$$

where v_i^t is current particle velocity, v_i^{t-1} is previous particle velocity, w is inertia factor, c_1,c_2 are user-defined constants, p_i^t is current pbest of particle i, and g^t is current gbest of the swarm. Parameters that used in the PSO technique are listed in Table I.

TABLE I. PSO PARAMETERS

Parameter	Range
Inertia weight (w)	0-1
r_1, r_2	0-1
c_1, c_2	2.05
Iteration numbers	1000
Swarm size	49

V. SIMULATION RESULTS

To demonstrate proposed work, the solution space is intended to keep parameters values that used in optimization within acceptable ranges. Ranges used in this paper are listed in Table II.

After these simulations are run at minimum (50µW) and maximum (500µW) input power levels and minimum (50Ω) and maximum (800Ω) emulated resistances, results of applying PSO on expressions (4-10) are shown in Fig. 8, where values of optimized L and t_{on} of each trial are taken after 1000 iterations or until the stop criteria is satisfied, it can be seen that the converter efficiency changes over range of emulated resistances where the maximum converter efficiency of 90.5% is achieved and 80% is achieved for lowest value of input power.

Fig. 9 shows a comparison between PSO simulation results of the optimized MPPT and simulation results of passive MPPT [9] for different values of emulated resistances (200 and 750Ω) over an extended power input range (50 µW-500 µW), it is clear from Fig. 9 that converter efficiency using PSO optimization is higher than the converter efficiency of passive MPPT simulation results [9] by almost 9.25% over an extended power input range (50 µW-500 µW) and reaches up to 90.8% for R_{em}=1000Ω. Also, it shows that optimized converter configuration has 3.5% higher efficiency than adaptive MPPT results [24] and gets higher for higher values of emulated resistances. It is worth noting here that the PSO program gives different results after each run.

VI. Conclusion

A novel mini notched turbine that can be used as feasible energy source and a methodology for optimizing maximum power point tracking system to improve the total efficiency for of low power energy harvesting systems have been introduced. The power generated from the mini notched turbine has the capability to deliver power to most low power applications at different speeds. Results demonstrate that maximum converter efficiency of proposed boost converter approach with PSO optimization is 90.5% for R_{em}= 750Ω which is 9.25% higher than passive MPPT [9] and 3.5% higher than adaptive MPPT [24] for same input power and 80% for lowest resistance R_{em}=50Ω. Another advantage is that the proposed design can be applied for extremely low power like photovoltaic, wind power, and mini notched turbine and because proposed work is valid for low emulated resistances. Therefore it can be applied with power sources with low load resistance.

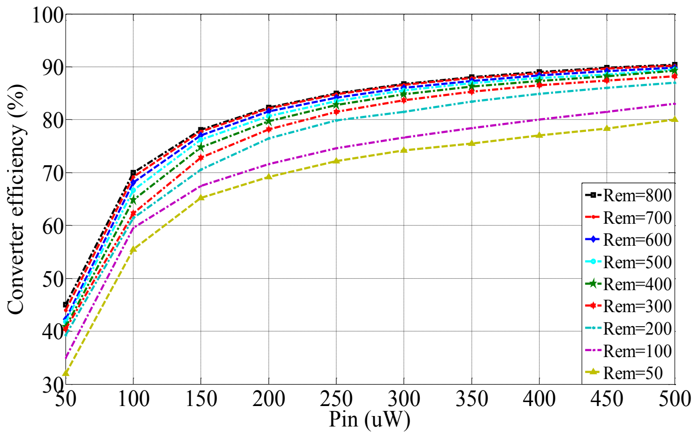

Fig. 8. Simulations at different values of R_{em} (50-800Ω) over P_{in} range (50 µW-500 µW).

TABLE II. PSO Parameters Values Used In Optimization

Parameter	Range
Emulated resistance	50-1500 Ohm
Input power	50-500 µW
Output Voltage	4.15-4.20V
Inductance	10-500µH
On time	5-100µsec
Diode	Vd=230-270mV
MOSFET	R_{on}=0.344Ω, M_g=650pf, C_{oss}=35pf

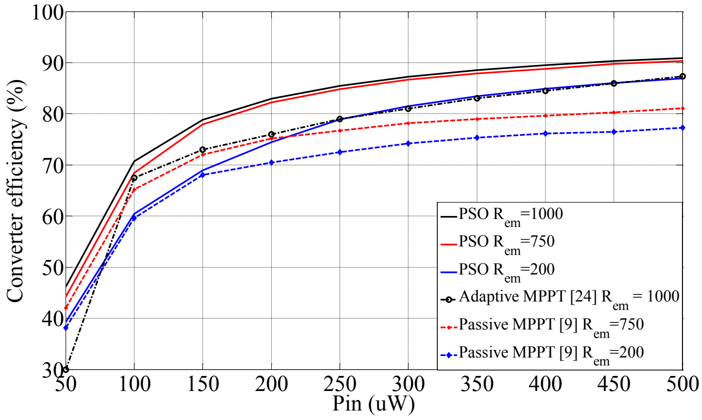

Fig. 9. PSO simulations results vs. simulations results of passive MPPT [9] of converter efficiency for R_{em} (200 and 750Ω) and simulation results of adaptive MPPT [24] for R_{em}= 1000 Ω.

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