Optimization of a Wearable Power System

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***Abstract*-In this paper the optimization of wearable power system comprising of an IC engine, motor/generator, inverter/rectifier, Li-battery pack, DC/DC converters, and controller is performed. The Wearable Power System must have the capability to supply an average 20W for 4 days with peak power of 200W and have a system weight less then 4kg. The main objectives are to select the engine, fuel and battery type, to match the weight of fuel and the number of battery cells, to find the optimal working point of engine and minimizing the system weight. The minimization problem is defined in Matlab as a nonlinear constrained optimization task. The optimization procedure returns the optimal system design parameters: the Li-polymer battery with eight cells connected in series for a 28VDC output voltage, the selection of gasoline/oil fuel mixture and the optimal engine working point of 12krpm for a 4.5cm^3 4-stroke engine.**

I. INTRODUCTION

A Wearable Power System is an electrical power source that can be carried easily on the body. In 2007, the USA Department of Defence (DOD) announced the Wearable Power Competition with intent to encourage teams and individuals to build a power system with the capability to supply an average of 20W for 4 days (with peak power of 200W) and have a total system weight of less than 4kg. The primary purpose of such a power supply is to be implemented in infantry solder’s equipment but also it could be used in many other commercial applications. Providing power for a limited time and being quite heavy, batteries, as the present choice, are not very convenient for a soldier wearable system. Fuel cells could be another solution as they have high specific energy, high efficiency and improved environmental performance and they can be incorporated into rechargeable energy storage systems. However, besides all these advantages, fuel cells need a large amount of hydrogen, which is difficult to store in lightweight fashion, so they are not promising candidate to meet construction requirements [1]. That is why the combination of Internal Combustion (IC) Engine and battery packages for energy storage and energy generation has been investigated.

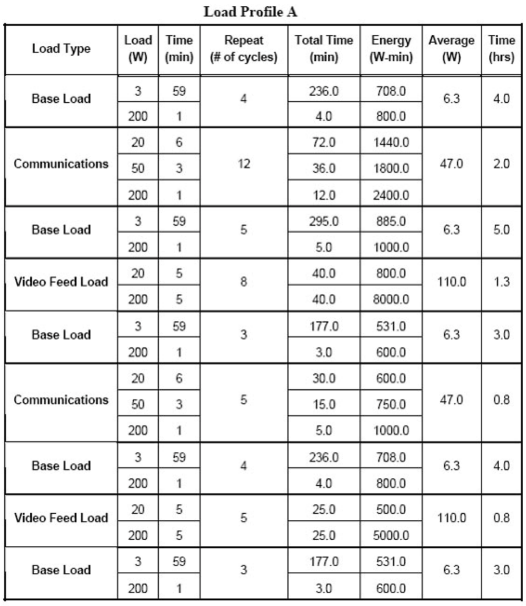
With the aim of developing a high efficiency and relatively light weight power system that will meet variety of power demands, the small engine is used to extract the energy from fuel into mechanical energy and the small generator is then used to convert the mechanical power to electrical power. To produce more energy from combustion, high energy density fuels are considered. The main objective is to select engine type and size, fuel and battery type and to match the weight of fuel and the number of battery cells in order to satisfy all input conditions and to find the optimal working point of engine when it is operated and the minimal overall weight.

The first part of this paper presents the requirements defined by the competition rules, the system description and behaviour and the optimization problem of wearable power system. Respectively in the second and third sections, the approach to optimization and the Matlab results are discussed. The conclusion summarizes the final design parameters returned by the Matlab optimization procedures and new optimization steps planned to be performed in a more general fashion.

II. WEARABLE POWER SYSTEM

A. *Requirements*

Minimum power delivery requirements for the system are: time duration of 96 hours, voltage output of 14V and 28V, average power of 20W, peak power of 200W [2]. According to the competition rules, each wearable power system is going to be tested against a specific load profile during the bench test. Three types of load repeat throughout the test: Base Load, Communications Load and Video Feed Load. The Video Feed Load is most critical part as the system must support 20W-200W power periods taking place every 5 minutes for up to 1 hour. In Fig.1, the table with details describing a 24-hour Load Profile is presented [3].



Load Profile A

Load Type	Load (W)	Time (min)	Repeat (# of cycles)	Total Time (min)	Energy (W-min)	Average (W)	Time (hrs)
Base Load	3	59	4	236.0	708.0	6.3	4.0
	200	1		4.0	800.0		
Communications	20	6	12	72.0	1440.0	47.0	2.0
	50	3		36.0	1800.0		
	200	1		12.0	2400.0		
Base Load	3	59	5	295.0	885.0	6.3	5.0
	200	1		5.0	1000.0		
Video Feed Load	20	5	8	40.0	800.0	110.0	1.3
	200	5		40.0	8000.0		
Base Load	3	59	3	177.0	531.0	6.3	3.0
	200	1		3.0	600.0		
Communications	20	6	5	30.0	600.0	47.0	0.8
	50	3		15.0	750.0		
	200	1		5.0	1000.0		
Base Load	3	59	4	236.0	708.0	6.3	4.0
	200	1		4.0	800.0		
Video Feed Load	20	5	5	25.0	500.0	110.0	0.8
	200	5		25.0	5000.0		
Base Load	3	59	3	177.0	531.0	6.3	3.0
	200	1		3.0	600.0		

Figure 1. Example of a 24-hour Load Profile (Bench Test).

B. *System Description*

The block diagram of the wearable power system is presented in Fig. 2. The system consists of the batteries and the fuel tank for energy storage, the engine for extracting the energy from the fuel by combustion and converting it to mechanical rotation, the three-phase generator with inverter

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output for mechanical to DC electrical power conversion, power electronics converters for adjusting the voltage levels and the controller for monitoring and regulating all changes inside the system.

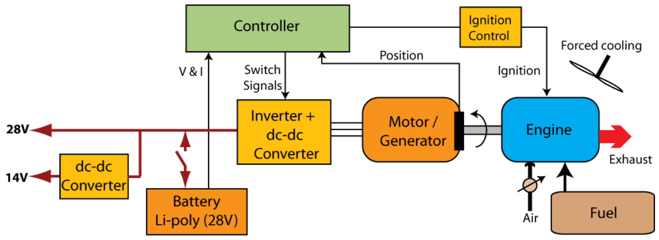

Figure 2. Wearable Power System.

The engine should be small and has relatively high efficiency to provide enough electrical power for the critical output load situations. It is a four-stroke, air-cooled engine that can be run under various throttling conditions. This type of engine is typically used in model aircraft. The corresponding fuel consumption should be as low as possible so a reasonable fuel weight can satisfy the four days load profile and the used fuel has to have high heating value. Two fuel mixtures that can be burnt in small engines are considered as the possible solutions for the system: the first methanol/oil, and the second gasoline/oil. The calculation is performed with the assumptions of 20MJ/kg for the heating value of the methanol mixture and 43MJ/kg for the gasoline/oil mixture. The real heating value depends on the amount of oil burnt in combustion process e.g. in the case of the methanol mixture, it lies somewhere between 17MJ/kg and 22.6MJ/kg.

A three-phase Permanent Magnet Synchronous Generator (PMSG) is attached to the IC engine. PMSG is an ideally suited machine for the task of electro-mechanical conversion as it has small size, low-weight and high efficiency. The output voltage from PMSG is proportional to rotating speed of alternator shaft. The PMSG machine works in a motor mode for short time, which is enough to start the engine. The AC/DC interface between PMSG and DC link is accomplished with a simple, six-switch MOSFET inverter/rectifier. The high efficiency is coming from the availability of low on-resistance MOSFET transistors.

Secondary batteries are continuously improving and are one of the most promising power systems today. Therefore advanced rechargeable Li-based batteries are chosen as battery storage in the wearable power system in Fig. 2. The properties used for selection of a battery system are gravimetric energy density, capacity, operating voltage, operating temperature, service life, weight per battery cell, and maximal charge/discharge current. The implemented DC/DC converter is a high efficiency (90-95%) buck converter.

Engine control is implemented as the state-machine consisting from the following states: initialization, no-engine running where the load is supplied solely by battery, engine start, engine run, engine stop, engine start fail, and shutdown. Tasks of supervisory part are system measurements, battery state of charge/discharge monitoring, fuel reserve estimation, cooling system control, power minimization.

C. *System Behavior*

The way the system functions can be simply described in following manner:

Engine turned off: The first case is when engine is turned off and the power output is supplied only by batteries; the batteries provide energy to the output as long as their state of charge (SOC) is above 20%; SOC is the amount of chemical energy stored in battery.

Engine turned on: The second case is when the engine is turned on to charge batteries and to provide the power to the output. The engine is stopped when the batteries are charged to 80% SOC as it is not possible to achieve full charging, since this would require the engine to be run at reduced speeds, low power and a low efficiency operating point.

D. *System Modeling*

Engine and generator measurements have been conducted to provide the mechanical/electric power, the fuel flow and the engine and generator efficiency as functions of speed characteristics. The measured data were used to interpolate the functions that define the corresponding dependences. Interpolation is done using Matlab polynomial fitting method. The exponents of polynomials are chosen to try to get functions that correspond to real dependences as close as it is possible.

Equations (1)-(7) are used to mathematically describe the system. To simplify the system in a first step, the engine, generator, inverter and converter were seen as the blocks characterized by the values of their power efficiency.

Equations (1)-(3) concern the power equilibriums inside the system.

$$W_{fuel} = LHW\cdot m_f \tag{1}$$
$$P_{el1} = W_{fuel}\cdot eff_{EG} \tag{2}$$
$$P_{el2} = P_{el1}\cdot eff_C \tag{3}$$

where LHW is the low heating value of the used fuel in J/kg, m_f is the fuel flow in g/min, W_{fuel} is the power produced by fuel burning, eff_{EG} is the efficiency of generator and engine together, P_{el1} is the electrical power at the output of generator, eff_C is the efficiency of DC/DC converter and P_{el2} is the electrical power at the output of converter or at the input of battery units and load.

The battery is modelled as a voltage source with the nominal voltage value E_b and an internal resistance R_b. The battery's discharging and charging currents are described by (4) and (5) coming from the power equilibrium at the battery input/output ports. So $P_{b,in}$ is the power for charging the battery units while $P_{b,out}$ is the power that the battery units provide.

$$I_{b,CHG} = 0.5\cdot(-E_b/R_b + ((E_b/R_b)^2 + 4\cdot P_{b,in}/R_b)^{1/2}) \tag{4}$$
$$I_{b,DCHG} = 0.5\cdot(E_b/R_b - ((E_b/R_b)^2 - 4\cdot P_{b,out}/R_b)^{1/2}) \tag{5}$$

The equations (4) and (5) are used for calculating the battery state of charge (SOC) and the state of discharge (SOD) [4].

When engine is turned off, the battery storage solely provides power to the output. On the other hand when the battery state of charge is less then 20% the battery is at its minimum level to ensure that the engine can be started. The power equilibriums in these ways of functioning are described by (6) and (7).

$$P_{out} = P_{b,out} \quad (6)$$
$$P_{el2} = P_{out} + P_{b,in} \quad (7)$$

The number of batteries in series is calculated by (8), to achieve the desired output voltage V_{out} of 14V or 28V.

$$n = [\, V_{out}/E_b] \quad (8)$$

For solving the system model, all previously defined parameters must be known. The battery data sheets provide the information about the different battery types, while the measurements are conducted to determine the engine/generator characteristics: the dependencies of the mass fuel flow, the efficiency and the output power on the different speeds of shaft.

E. *Optimization Problem*

Optimization of the wearable power system can be seen as making the compromise between the number of parallel strings of series connected batteries in the storage system, the total volume of fuel and the type of engine. The battery storage must handle the delivered current at its input determining the minimal number of parallel strings of batteries in the storage system while the output voltage determines the number of batteries per parallel path. In general, having more fuel, a smaller engine (with lower efficiency) can be used implying less battery cells in parallel, and vice versa having more cells in parallel heavier engine can be implemented (with higher efficiency) and less fuel would be necessary. The optimization problem is specified by the function of the total weight of system that includes in the first approximation only the weight of fuel, engine, generator and batteries.

The crucial part of optimization problem lies in optimizing the battery storage to meet power-speed requirements of given engine and PMSG drive. Tending to have the smallest number of batteries as is possible, the right battery type must be selected. The battery storage and fuel storage are complementary energy sources and the aim of optimization task is finding the optimal three-fold data set of rotational speed of generator, number of battery cells, and fuel weight.

III. APPROACH TO OPTIMIZATION

The optimization problem is specified by the function of the total weight of system that includes in the first approximation only the weight of fuel, engine, generator and batteries. Minimization of the function is performed under the absolute and side constraints derived from the mathematical model of system and the natural bounds of system parameters. The most of constraints are nonlinear therefore finding the minimum of total system weight can be observed as the nonlinear constrained optimization problem.

The general problem description is to minimize the objective function F(X) subjected to the set of nonlinear constraint functions: $g_i(X) <= 0$, i= 1..p.

In the literature, constrained optimization problems are solved either by direct methods or by using unconstrained optimization. For the purpose of comparison and checking the correctness of results, two programs, one based on Sequential Unconstrained Minimization Techniques (SUMT) and another based on direct method, Sequential Quadratic Programming (SQP) are implemented with Matlab. Matlab is chosen as software tool as it already possesses useful built-in functions for optimization.

A. *Sequential Unconstrained Minimization Techniques*

In constrained optimization, the common way of solving the problem is to transform the original problem into an easier sub problem. A large class of methods translate the starting constrained problem to a basic unconstrained problem using a penalty function for constraints. The constrained problem is than solved using the sequence of parameterized unconstrained optimizations that converge in the limit to the constrained problem. One of methods for solving constrained problem using unconstrained optimization is Interior Penalty Function Method that belongs to the class of Sequential Unconstrained Minimization Techniques (SUMT) defined in [5]. The Interior Penalty Function Method penalizes the objective function as the design approaches a constraint and constraint violation is never allowed (comparing to Exterior Penalty Function Method). So the initial point and all subsequent points are feasible meaning that they satisfy both side and absolute constraints and the sequence of feasible solutions are produced. This feature is very useful as in physical case some parameters must belong within some range as they are meaningless otherwise e.g. weight of the system can not be less then zero. This method has also showed to be good in some real industrial applications [6]. Matlab built-in function fminsearch() was used for the implementation of the Interior Penalty Function Method.

B. *Sequential Quadratic Programming*

The other approaches of solving the constrained optimization problems are direct methods that deal with the constraints directly in the search for the optimum. Also the side constraints are treated separately from the general inequality constraints. In mathematical software, Sequential Quadratic Programming (SQP) is one of the most popular direct algorithms. The basic idea of SQP is to model non-linear problem at a given approximate solution $X^{(k)}$ by a quadratic programming sub problem (that is easy to solve in the sense that there are good procedures for their solution), and than to use that solution to this problem to construct a better approximation $X^{(k)}$ [7]. This iteration should converge to a real solution $X^{(*)}$. Matlab possesses the built-in function fmincon() based on SQP that attempts to find a constrained minimum of a scalar function of several variables starting at an initial estimate. The SQP is not a feasible-point method meaning that, neither the initial point nor any of iterates need to be feasible. For the case of the Wearable Power System, the design variables must fulfill at least the side constraints so the every iteration for which $X^{(k)}$ didn't satisfy the side constraints is disregarded.

IV. RESULTS

The current experimental set-up for measuring the characteristics of engine and generator consists of the OS-

FS-26 Surpass IC (4.5cm^3) engine and the LMT-2230/18 HA PMSG generator with the datasheets given in [8, 9]. The engine and generator are connected together and the set-up is connected via the sensors to computer so it is possible to efficiently collect data measurements. Two experiments have been conducted, one with the methanol/oil and the other using gasoline/oil mixture as a fuel.

A. Results for Methanol/Oil Mixture

According to the measured values of the electrical power at the output of generator, the fuel mass flow and the speed of shaft, the corresponding dependencies (the output power of generator, the engine/generator efficiency and the fuel mass flow functions of speed) derived using polynomial fitting methods are shown in Fig. 3, 4 and 5. Depending on the heating values of the used fuel, the efficiency of generator and engine system is not directly measured but derived from the measured output power and mass flow values at the different speeds.

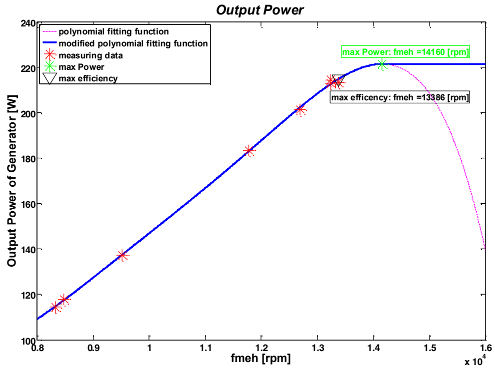

Figure 3. Output Power of Generator vs. Speed of Shaft.

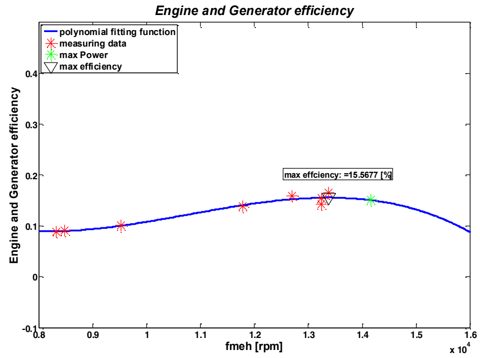

Figure 4. Efficiency of Engine and Generator vs. Speed of Shaft.

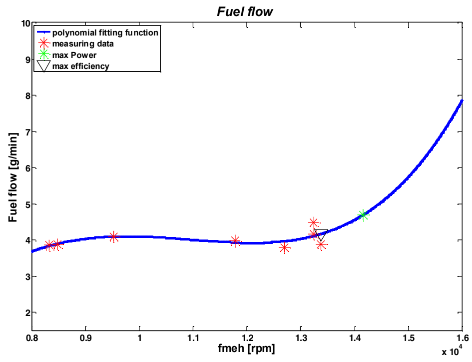

Figure 5. Fuel mass flow vs. Speed of Shaft.

The exponents of polynomial fitting functions were chosen so the resulting dependencies in Fig.3, 4 and 5 describe the physical system in the correct manner: for high speeds the power and efficiency drop while fuel mass flow drastically increases; for the certain speeds the power and efficiency reaches the maximum; at low speeds the power and efficiency are low; and the speed for the maximum efficiency is below the speed for maximum power. As the highest speed of 16000 rpm is not possible to achieve with the OS-FS-26 Surpass working on methanol, the final fitting function for the output power dependency on speed is modified so that it doesn't follow the polynomial function above the maximal power any more but it stays constant. The maximal efficiency is 15.5% and it is achieved for speed of 13386 revolutions per minute.

Procedures were run for both possibilities of output voltage, 14VDC and 28VDC and for four different battery types: Li-Ion ANR26650 (70g per cell), two options of VARTA Li-Polymer batteries (17g and 24g per cell) and KOKAM Li-Polymer battery type (115g per cell). The data sheets can be found respectively in [10], [11], [12]. None of these battery types satisfies all the desired features: small weight, high maximal charging current and high nominal voltage. Regarding the minimum weight, both algorithms have returned the KOKAM Li–Po as the best choice, ANR26650 Li-Ion as the worst choice while VARTA batteries were in the middle.

The KOKAM Li-Polymer battery type is probably the type of battery that will be finally chosen in the system. These batteries are allowed for the maximal charging current so minimal number of batteries in parallel is needed and results shows that for 14VDC and 28VDC output voltage, the same system weight can be achieved. Therefore 28VDC mostly likely will be selected as this request in lower currents and possibly lower electrical losses. It also shows that the battery type with the highest gravimetric energy (VARTA) is not the optimal solution.

For each found optimal system design parameter set, a simulation is performed to check if optimized system behaves well under a random 96-hour Load Profile. A good behaviour means that an optimization method has returned the design three-fold set [speed of shaft, number of cell in parallel, fuel weight] such that there is enough fuel and enough battery storage to provide the needed power for the specific 96-hours Load Profile. The zoomed plot of Matlab simulation in the case of output voltage of 28VDC and KOKAM battery type is presented in Fig.6. The plot shows the Load Profile (black line), the battery state of charge (SOC, red line) and the engine on/off states (violet line). When the engine is on, the engine state is zero, the battery state of charge (SOC - red line) increases. When the state is high, the engine is off, SOC follows the Load Profile (black line) meaning that if output power is low around 3W the batteries discharge slowly and for the high peaks of output power, batteries discharge very fast.

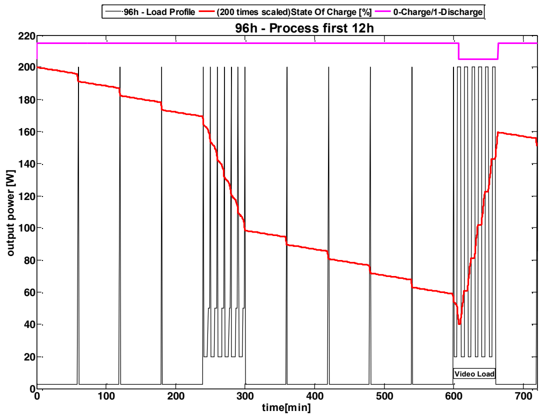

Figure 6. Simulation results for the case of 28VDC at the output and KOKAM battery type.

The optimization report for the KOKAM batteries and the output voltage of 28V is given in Table I. The final results of the Matlab optimization for the wearable power system with the OS-FS-26 Surpass engine and LMT 2230/18 HA PMSG generator are: voltage output of 28VDC, eight battery cells in series (KOKAM type), running the engine around the point of the maximal efficiency. The report includes also the following results: the engine working operating point, the total fuel consumption, the intervals of charging periods and the remaining fuel. The optimization is done with the margin so the calculated total needed mass of fuel is showed to be more then enough for 4-days Load Profile. The simulation proved that such system can accomplish the required power demands but not the weight requirement as the total system weight in the best case was more then 4kg.

In the summary, with the methanol mixture as the fuel and for the available engine and generator data measurements, both optimization procedures have showed that the constraint related to the maximum weight of the system (4kg) could not be realized.

B. Results for Gasoline/Oil Mixture

The weight constraint being not satisfied points out that the better results can be expected for the fuel with higher heating value e.g. gasoline mixture with 43 MJ/kg. To prove this assumption, new experiments are done for the same engine-generator system and using the gasoline/oil mixture. Taking 43 MJ/kg as the fuel heating value in the calculations, according to the data measurements of the output power, the fuel mass flow and the speed of shaft, the engine characteristics were interpolated in the similar manner as it was presented for the methanol case. The fitting defined the maximal engine-generator efficiency to be 12.9% at the speed of shaft equal 11599 revolutions per minute. The simulation is done for the KOKAM Li batteries to examine the behaviour of the system under the 96 hours Load Profile. The final report returned by Matlab simulation is given in Table II.

As it was expected, the simulation has shown that the all required constraints can be satisfied by using the gasoline instead of methanol. The engine operating point is determined to lie above the speed of the maximal engine efficiency, the total system weight is less then even 3kg and the remaining fuel after 96 hours is greater then zero. So the suggested wearable power system under the first approximation and simplification steps can function according the given demands.

C. Sequential Quadratic Programming vs. Sequential Unconstraint Optimization Technique

SQP and SUMT do not return completely the same design parameter sets. As it has been already noted, SUMT need a feasible point to start optimization routine and because of that it takes longer time to finish optimization with the output comparable to the output of program based on SQP method. Also SQP looks more stable as it finds for all cases the same operating engine and generator point. On the other side, SUMT returns not exactly but approximately the same point.

The important fact is that there is no guarantee for both methods, that they will find the global minimum for the search space. For this reason the multi-start SQP and SUMT algorithms were implemented meaning that initial starting points were chosen throughout the design variable space to start the algorithms several times and after finding the local minimum points for each starting point the best ones were returned by the functions.

TABLE I
THE MATLAB OPTIMIZATION REPORT FOR METHANOL

System Weight	4010 g
Fuel Consumption (96-hour Load Profile)	2271 g
Total Fuel Weight	2442 g
Remaining Fuel	171 g
Engine Operating Point	
Engine Speed	13121 rpm
Mass Fuel Flow	4.07 g/min
Engine and Generator Efficiency	15.5 %
Battery Information	
Battery Type	KOKAM
Output Voltage	28 VDC
Power at Battery Input	200 W
Number of Cells in Series	8
Number of Parallel Battery Strings	1
Charging Periods	
Number of Charging Periods	15
Maximal Duration of Charging	58 min
Minimal Duration of Charging	27 min

TABLE II
THE MATLAB OPTIMIZATION REPORT FOR GASOLINE

System Weight	2972 g
Fuel Consumption (96-hour Load Profile)	1305 g
Total Fuel Weight	1404 g
Remaining Fuel	99 g
Engine Operating Point	
Engine Speed	12358 rpm
Mass Fuel Flow	2.34 g/min
Engine and Generator Efficiency	12.4 %
Battery Information	
Battery Type	KOKAM
Output Voltage	28 VDC
Power at Battery Input	200W
Number of Cells in Series	8
Number of Parallel Battery Strings	1
Charging Periods	
Number of Charging Periods	15
Maximal Duration of Charging	56 min
Minimal Duration of Charging	27 min

The project being still in development phase implies that the found total weights of system are useful for mutual comparison of designs with different battery types but does not present the final design suggestions about weight issues. The programs should be run with more precise data measurements and with more starting details for the system that will be available in the future.

CONCLUSION

The paper gives the starting point on how to design the wearable power system for the given specifications. Under the assumption of using the chosen Li-based rechargeable batteries, the OS-FS-26 Surpass engine and LMT 2230/18 HA PMSG generator, the system is modelled by equations that are implemented in Matlab optimization programs. The optimization of the system is presented as the problem of finding the minimum of function subjected to nonlinear constraints. Two methods, Sequential Quadratic Programming and Sequential Unconstrained Optimization Technique are implemented with Matlab and compared. The optimal design results returned by Matlab optimization and simulation procedures are: an output voltage of 28VDC, eight KOKAM Li batteries in series, the optimal engine operating point around the point of maximal efficiency and the gasoline/oil mixture as fuel.

The Matlab program works just for the one engine type as it deals with one discrete set of input data from engine and generator measurements. The optimization of a wearable power system will be investigated as a more general problem in future. By collecting the data about different engines, together with examining the battery types of different manufactures, the 3D curves that describe the dependency of battery weight on capacity and nominal voltage and the dependency of engine efficiency on weight and speed, will be interpolated to run optimization for finding the wearable power system of minimal weight. The new optimization program will return the engine with optimal characteristics not necessarily the exact type of engine, also the fuel type, properties of battery storage and selection of 14VDC or 28VDC voltage output.

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