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Fuel Consumption Analysis of Hybrid Excavator Using Electric Swing Motor

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Abstract

This study evaluates the effect of hybridization on excavator when the hydraulic swing motor of a conventional excavator is replaced by an electric motor. The powertrain structure and the working environment of the conventional system are introduced, and the fuel consumption of the conventional excavator is obtained from experimental data for four specific working schedules. Two structures of hybrid excavators are introduced, and the best fuel consumption is solved by Dynamic Programming, which guarantees the minimum fuel consumption for the same schedules. The results showed that the fuel consumption of the hybrid excavator can be saved by about 9~17% depending on the working schedules and that the fuel consumption decreases as more electrical power of swing motor is used for rotation.

Keywords: Optimization, Simulation, State of Charge, Energy Consumption, electricity

1 Introduction

The growing concerns about energy and environmental issues have served as the stimulus for developing high energy efficient and environment-friendly vehicles and construction equipment. Recently, researches on hybrid electric vehicles have made much progress, and several automotive companies are establishing mass production systems for passenger hybrid electric vehicles. However, further progress is still needed in the area of hybridization of construction machinery, especially the conventional hydraulic excavator. Recently, research on the structure of powertrain, control strategy and energy management of the hybrid system in hydraulic excavators has been carried out [4-7]. The control strategy, which determines the working state of the components in the power system, directly and affects the energy consumption of a hydraulic excavator, ultimately, becomes one of the major concerns in researches of hybrid system [4]. A few companies in Japan, Europe and the USA introduced hybrid excavator of various structures and presented a development plan.

To evaluate the effect of hybridization on the conventional excavator, we analyze the fuel consumption of the hybrid excavator proposed in this study by Dynamic Programming (DP), which has been applied to solve the minimum fuel consumption problem of passenger hybrid electric vehicles [1-3]. In this study, the DP approach is used for analyzing the fuel consumption of the hybrid excavator, and the fuel consumption results are compared with that of the conventional excavator under the same working schedules.

This paper is organized as follows. In section 2, the powertrain system of the conventional excavator and operating characteristics are introduced and section 3 presents the two hybrid excavators for analyzing fuel economy. The methodology to analyze the fuel economy of proposed systems is addressed in section 4 together with needed experimental data. And also simulation results are shown according to hybrid type in section 4. Finally, conclusions are provided in section 5.

2 Conventional Excavator

2.1 Structure of Powertrain

A structure of the power system of a conventional excavator (C.E.) is shown in Fig. 1. The engine drives the hydraulic pump directly, which converts mechanical power to hydraulic power. The main control valve (MCV) transmits the hydraulic power to actuators, namely, the boom, arm, bucket, swing and traction systems, according to operating signals. The hydraulic energy produced by the pump is delivered as flow rate and pressure for the hydraulic actuators, which can convert the hydraulic power to mechanical power. This kind of conversion process inevitably leads to substantial energy conversion loss.

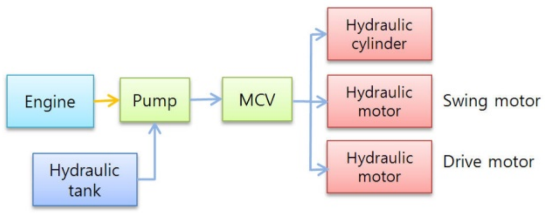

Figure 1: Schematic diagram of conventional excavator

2.2 Working Characteristics of the conventional System

To analyze the fuel consumption of the hybrid excavator (H.E.) under several assumptions, first, it is necessary to obtain data such as the operating characteristics of the conventional system for a certain working schedule. We analyzed the test data of engine output torque, output speed, fuel consumption and actuator operation. And then we calculated the engine operating point and the power consumed by the swing part.

Figure 2 shows the one cycle operating state of the engine when the excavator had completed an actual 180 degree digging work. Digging, rotating, dumping from a bucket, and relocating are consecutively performed at the same place for about 18 seconds. The figure shows that the engine torque fluctuates widely with working state while the speed varies within 10% of the maximum speed. These results are different from the operating characteristics of a vehicle system. Output torques sharply increase at a fast pace to meet the power demanded from the main pump. Hence a capacitor, which has a fast charge-discharge speed and long cycle-life, is used as an electric accumulator to balance the fast power fluctuation in the hybrid system [4].

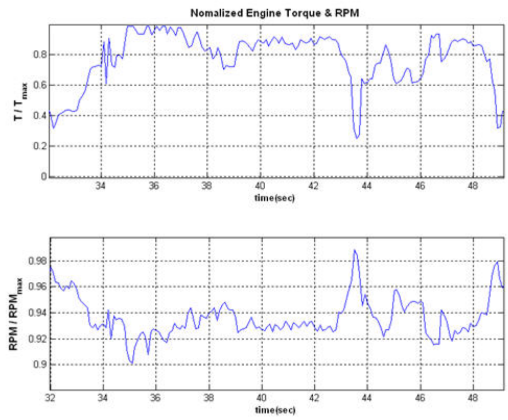

Figure 2: Normalized engine output torque and speed of conventional excavator

Figure 3 shows that engine operating points are distributed in a limited speed range, because the engine, as the primary power source, is controlled to output maximum power by a few methods that are using the governor and input signal of electric current.

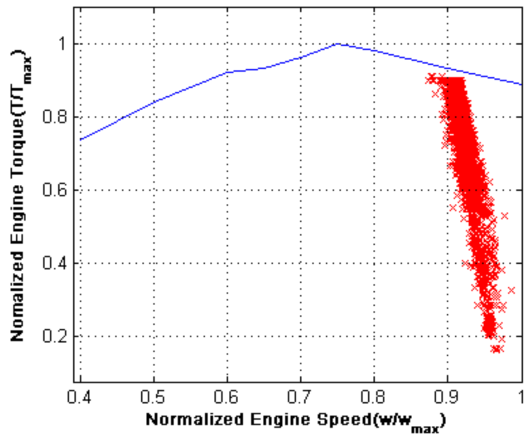

Figure 3: Operating points of conventional excavator during one working cycle

To check the validity of using engine BSFC (Brake Specific Fuel Consumption) map, we compared the experimental fuel consumption with fuel consumption calculated using the BSFC map for one working cycle (18 seconds). The results presented in Table 1 show the error to be around 1.2%.

Table1: Comparison of fuel consumption

Method of estimation	Fuel Consumption(g)	Error
Experimental FC	87.0582	Ref.
Operating Points on the Engine Map	86.0520	-1.15%

3 Hybrid Excavator

Two types of hybrid structures are introduced for the hybrid excavator. The first one is the parallel type, in which the electric motor supports the engine to operate the hydraulic pump or converts the engine's redundant mechanical energy to electrical energy; the other is the compound type, in which an electric motor-generator is used as the engine power assistant and another electric motor, which can convert the braking energy of the swing system to electric energy, is used instead of the hydraulic swing motor. In case of series type, the engine power is used only to generate electricity, and electric motors of each actuator drive the boom, arm, bucket and swing systems. In this research, analyze the parallel and compound systems.

3.1 Parallel Type Hybrid System

The parallel type system has synchronized engine and assistant motor output shafts, which allow the connection of the final output shaft to the input shaft of the main pump. It can be developed and maintained at a lower cost than the other hybrid system because the electric power system is only attached to the existing internal combustion engine in Fig. 4. But it has disadvantages: an additional hydraulic device is needed to recover the loss power and fuel economy is low.

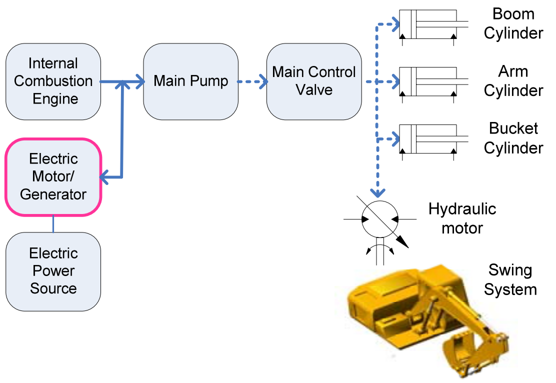

Figure 4: Schematic of parallel type hybrid excavator

3.2 Compound Type Hybrid System

Figure 5 shows the schematic of the compound hybrid excavator. This is a complex system which combines the parallel and series type. The key feature of the compound type is that the hydraulic swing motor is replaced by an electric one. When the swing part decelerates, the electric swing motor can be used to generate electricity by producing a negative torque. Energy conversion loss can be decreased by the basic structural alternations of the conventional hydraulic system. The control strategy for the system, however, becomes increasingly sophisticated.

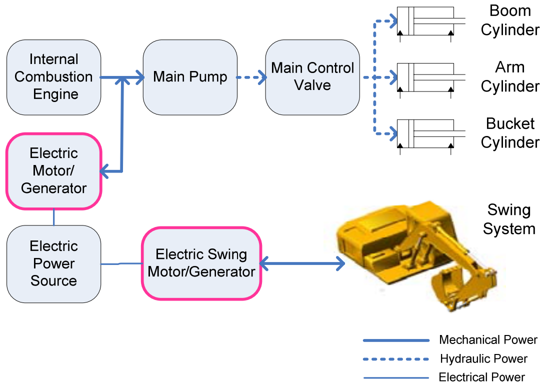

Figure 5: Schematic of compound type hybrid excavator

4 Fuel Consumption Analysis Methodology

4.1 Acquisition of test data

To realize the minimum fuel consumption of the hybrid excavator by using DP, we need a reference working schedule and data on the required torque and speed at each time. Four working schedules were obtained from actual operation records of the conventional excavator, and the hydraulic swing motor power was calculated for these working schedules. Figure 6, for instance, shows the total engine output torque of a conventional system and the engine torque, which is required for rotation of the swing system. And figure 7 shows the swing motor torque and speed during 180degree rotation dump , which is repeated five times.

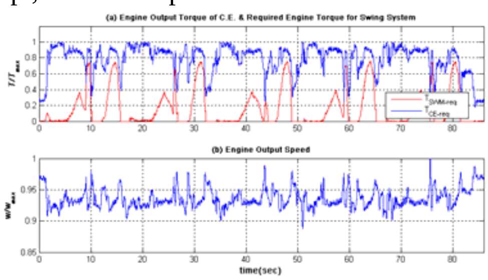

Figure 6: Engine output torque and speed by experiment

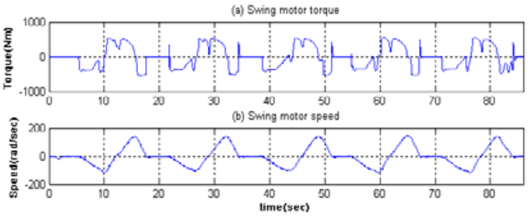

Figure 7: Swing motor toque and speed by experiment

The required power of the compound hybrid excavator to operate the main pump is smaller than the power of the conventional excavator because the pump of the compound H.E. does not have to supply mechanical power to the swing system. Therefore, we can calculate the required power, P_{HE_req}, to operate the main pump of the compound H.E. in Fig. 5.

$$P_{HE\_req} = P_{CE\_req} - P_{SWM\_req} \quad (1)$$

where, P_{CE_req} is the power to operate the main pump of the conventional system, and P_{SWM_req} is the power to operate the swing part.
Figure 8(a) illustrates the output power of the conventional excavator and the required power of the hydraulic swing motor. The required power for simulation of hybrid excavator can be calculated, as shown in fig. 8(b) by Eq. (1),

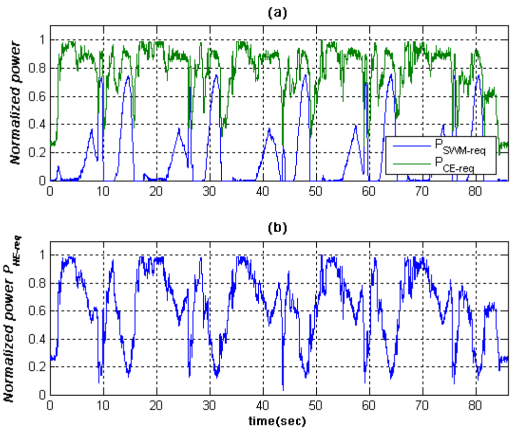

Figure 8: The required power for simulation of hybrid excavator

Table 1 shows the required energy of the swing system calculated based on the experimental data. The consumed energy by the swing part may be able to become intuitive information about regeneration. In other words, it is the maximum energy which can be recovered by the electric swing motor. The recovered energy, however, will be lower than the maximum energy because of the efficiencies of the electric motor and inverter.

Working Cycle	Total Energy (MJ)	Hybrid excavator (MJ)	Swing motor (MJ)	Ratio (%)
90P(60sec)	5.597	4.498	1.099	19.63
90S(67sec)	5.178	4.421	0.757	14.61
180P(86sec)	7.881	5.917	2.160	24.92
180S(86sec)	6.031	4.721	1.744	21.72

Table 1: Consumed energy by the swing part

In the compound hybrid excavator, P_{HE_req} calculated by DP can be represented as the sum of the engine output power, P_{en} and the engine assist motor power, P_{m1}, in eq. (2).

$$P_{HE\_req} = P_{en} + P_{m1} \quad (2)$$
$$T_{HE\_req} = T_{en} + T_{m1} \quad (3)$$
$$\omega_{HE\_req} = \omega_{en} = \omega_{m1} \quad (4)$$

The rotational speeds of the engine and assistant motor are synchronized because the electric motor for power assistance is directly connected to the engine output shaft. Therefore Eq. (2) is replaced by Eq. (3). And we were able to calculate the engine speed required in the hybrid system by using an engine dynamic model.
To analyze the SOC (State of Charge) of the electric power source (Super Ultra Capacitor), the following equations about electric power are needed.

$$P_{cap} = P_{el\_m1} + P_{el\_m2} \quad (5)$$
$$P_{SWM\_req} = \eta_{m2}^{k} \cdot P_{el\_m2} \quad (6)$$
$$P_{m1} = \eta_{m1}^{k} \cdot P_{el\_m1} \quad (7)$$

Eq. (5) shows that the charging / discharging power of super-capacitor, P_{cap}, is determined by the use of the assistant motor (m1) and swing motor (m2). In Eq. (6-7), the efficiencies of the assistant motor and swing motor, viz. η_{m1}^{k}, and η_{m2}^{k}, are numerically calculated by interpolating the motor-efficiency maps of each motor, which include the motor loss and the inverter loss. Further,

$$k = \begin{cases} 1, & recuperating \\ -1, & motoring \end{cases} \quad (8)$$

Finally, the derivative of SOC, namely, $\dot{SOC}$, can be calculated from the capacitor power and the current SOC.
The optimal control problem can be solved such that the fuel consumption is minimized by using DP because the correlation between the state variable and control variable can be obtained from

the quasi-static model of the compound hybrid excavator.

4.2 Dynamic Programming

Dynamic Programming was developed during the 1950's by Richard Bellman and has ever since been used as a tool to design optimal controllers for systems with constraints on the state variables and control inputs. For a given system, it can be used to find the optimal control input that minimizes a chosen cost function [7]. The Dynamic Programming theory, which has been used in automotive applications, can also be used to optimize the parameters of a power train. In this paper, by using DP, we predicted the minimum fuel consumption and SOC trajectory of a given hybrid system whose hydraulic swing motor has been replaced by an electric one.

In dynamic programming problems, the following discrete-time dynamic system is considered

$$x_{k+1} = f_k(x_k, u_k), \quad k = 0,1,\dots,N-1. \quad (8)$$

The dynamic states $x_k \in X_k \subset \mathbb{R}^n_\delta$ and the control inputs $u_k \in U_k \subset \mathbb{R}^m_\delta$ are discrete variables both in time (index k) and value (thus the subscript $\mathbb{R}^{\cdot\cdot}_\delta$ of the vector spaces). The control inputs u_k are limited to the subset U_k, which can depend on the states x_k, i.e., $u_k \in U_k(x_k)$. A specific control policy is denoted by $\pi = \{\mu_0, \mu_1, \dots, \mu_{N-1}\}$, and the cost of using π on the problem (8) with the initial condition x_0 is defined by

$$J_\pi(x_0) = g_n(x_N) + \sum_{k=0}^{n+1} g_k(x_k, \mu_k(x_k)) \quad (9)$$

With these definitions, the optimal trajectory π^0 is the trajectory that minimizes J_π [8].

$$J^0(x_0) = min\ J_\pi(x_0) \quad (9)$$

As an example of DP analysis, the optimal field and optimal trajectory are presented in fig. 9. The data are calculated for the operation of an arbitrary system, for a terminal time of 100sec, a target terminal SOC of 0.6, a time step of 1sec, and an SOC discretization of 0.001% of full charge. The target terminal SOC can be reached starting from an initial SOC lower than 0.65 and greater than 0.55. In this example, the initial SOC is 0.6 which will be the same as the final SOC.

The optimal field is the set of feasible points set at each time and SOC level. And the optimal trajectory is the route that guarantees the optimality of states at minimum cost under given conditions, which are the initial and final SOC.

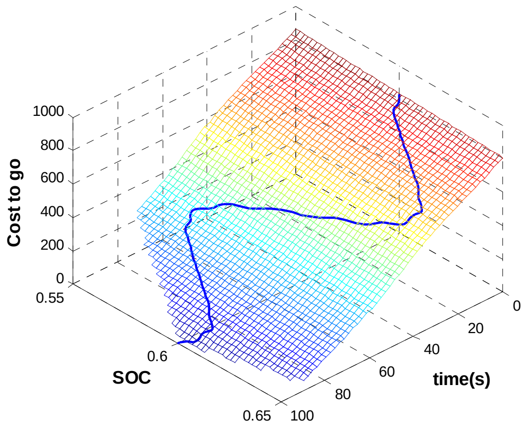

Figure 9: Engine output power and swing motor speed under real operation

4.3 Simulation Results

Research on hybrid excavator has been limited, and there has been also no point of reference, such as driving schedules used in vehicle simulator. The work situation of excavators varies with the working conditions and drivers considerably. Therefore, we assumed representative working cycles, which are repeated 90, 180 degree digging work of four working modes. They are different with working time and engine mode (Power mode, Standard mode). In this section, the analysis results for one cycle are demonstrated, and four results of fuel consumption calculated for the working cycles by MATLAB are presented.

4.3.1 Parallel system

In case of the parallel hybrid excavator, the fuel consumption is higher than that of the compound system because the parallel type does not have the recovery system and the engine alone has to supply the entire load power needed. In addition, the conventional engine is operated in the high efficiency region on the BSFC map.

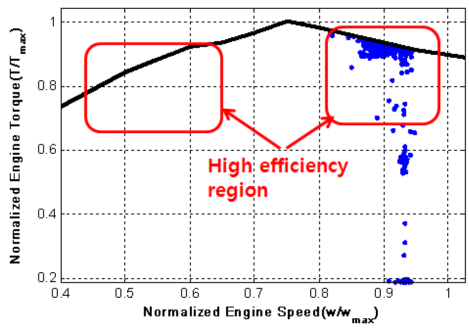

Figure 10: Engine operating points in parallel system

Figure 10 illustrates the distribution of the engine operating points during the 180 degree working cycle.

The optimal states of the engine and assistant motor are shown in fig. 11. The engine outputs almost all the required torque and the assistant motor rarely works to assist the engine, since the engine can be operated in the high efficient region when it has a high output power. (In case of parallel type, the maximum torque of engine was limited to 90%)

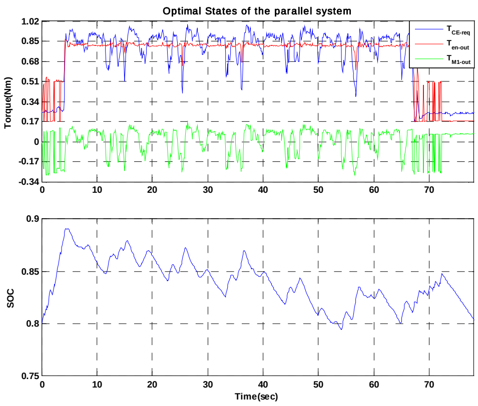

Figure 11: optimal states of engine, motor and SOC

4.3.2 Compound system

Figure 12 and 13 show the results of optimal states of the compound hybrid system solved by DP under the 180 degree dump working schedule. The engine repeatedly outputs more torque than needed as the swing system starts to do revolve, as shown in fig. 12. At this moment, the assistant motor generates electricity by using the surplus engine torque to operate the swing system. Taken as a whole, the assistant motor scarcely outputs any positive torque for load power to assist engine. The engine in this analysis was not sized down, and the conventional engine size it was used. Therefore, it may be more efficient for the engine alone to directly output the load power than for the motor and engine together to output the load power. Because of the engine efficiency, power recirculation is an inefficient operating condition.

The optimal SOC trajectory shown in Fig. 4 is repeatedly changed according to the operation of the swing system. In general, the SOC increases when the power of the swing system is negative, and decreases when the swing power is positive although the other motor-generator also affects the SOC. However, the engine outputs more torque than the required torque in the swing part to increase SOC when the swing part turns to the left in the initial stage. For optimality, the SOC is slightly increased to compensate the loss of energy in the future swing even when the swing motor does not operate.

Figures 14, 15 show that the results enlarged of fig. 12, 13 during one working cycle from 34second to 52seconde. In fig.14, the swing part utilizes electric power to turn to the left in region (1). In region (2), the electric swing motor works as the generator, so deceleration energy can be stored in the electric power source. Also, the swing part uses

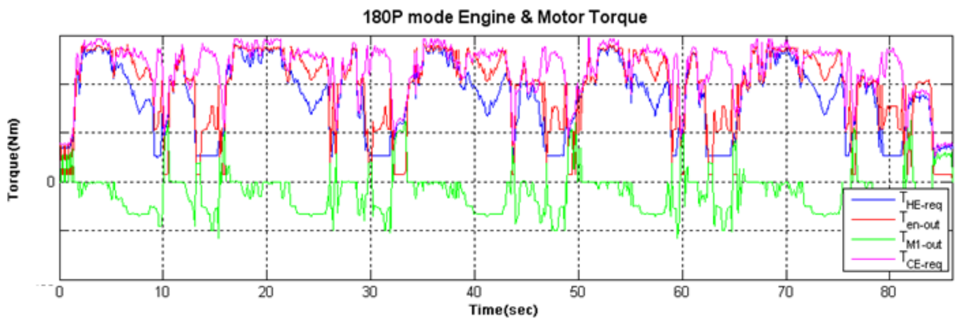

Figure 12: optimal states of engine and assistant motor

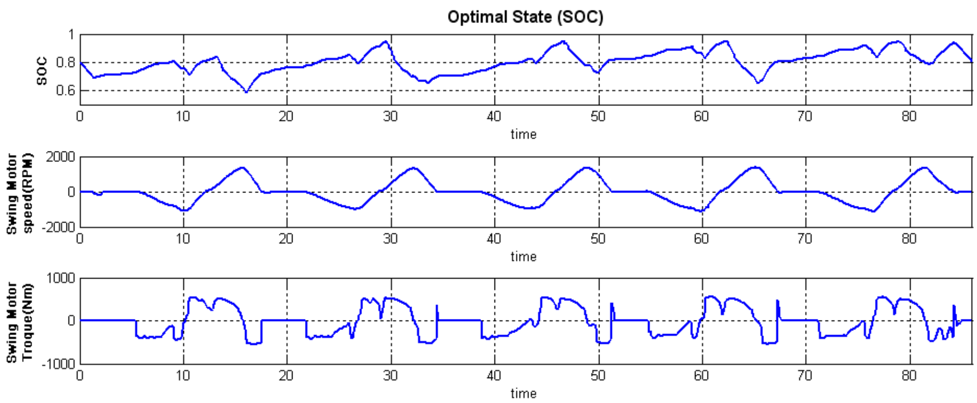

Figure 13: optimal states of SOC with swing part operation

power to turn in the opposite direction in region (3) and regenerates the electric source in (4).

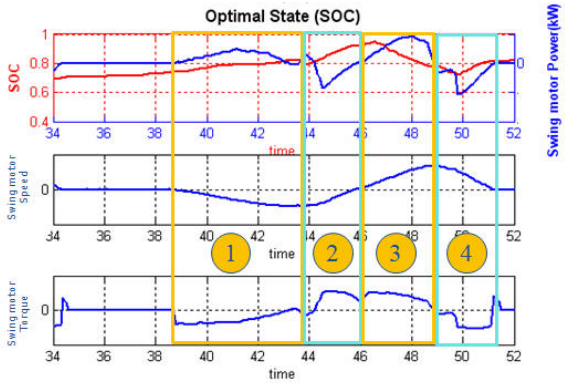

Figure 14: optimal states of engine, motor and SOC

Figure 15 illustrates the optimal working states of the engine and assistant motor. T_{CE_req} , T_{CE_req} are the required torques of conventional and hybrid excavators induced from section 4.1. Both the output torque of the engine, T_{en}, and the output torque of the assistant motor, T_{m1} are the optimal output states at each time during one working cycle.

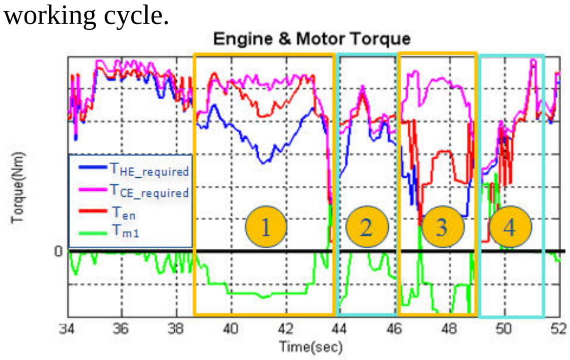

Figure 15: optimal states of engine, motor and SOC

The fuel consumption results of several working cases are summarized in table 2.

Table 2: comparison of fuel consumption according to several working cycles

Working Cycle	C.E.(g)	H.E.(g)	F.C. Decreasing (%)	SER (%)
90P(60sec)	349.61	303.57	13.17	19.63
90S(67sec)	332.55	302.81	8.94	14.61
180P(86sec)	494.31	410.96	16.86	24.92
180S(86sec)	393.28	340.00	13.54	21.72

Simulation results show that the compound hybrid excavator can achieve 9~17% less fuel consumption than the conventional excavator. If more electric power is used for the swing motor, fuel consumption can be reduced more in the compound hybrid excavator. In the case of the parallel type excavator, which cannot recover the braking energy of the swing system, the fuel consumption decreased by about 3~5%. In conclusion, because of the electric swing motor which can recover the loss energy, the fuel economy of the compound hybrid excavator is higher than that of the parallel type system.

5 Conclusion

In this paper, the effect of hybridization on the performance of an excavator was analyzed by the optimal control theory, Dynamic Programming. First, experimental data of the conventional excavator were obtained, and then analyzed to apply them in DP. Based on the simulation results, the fuel consumption and optimal working states of each part were predicted for four reference working cycles when the hydraulic swing motor had been replaced by an electric one. These results can be applied to develop the control strategy of the hybrid system. They can also be used to provide an optimal performance benchmark. The simulation results were provided, and the effectiveness of the hybrid excavator system that can increase the efficiency of the conventional hydraulic system was demonstrated. Lastly, we suggested a methodology to get the hybridization effects in other construction equipments or high load systems such as a train system and wheel loader, etc.

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