Power Control Algorithm for Hybrid Excavator With Supercapacitor

Tae-Suk Kwon, *Member, IEEE*, Seon-Woo Lee, Seung-Ki Sul, *Fellow, IEEE*, Cheol-Gyu Park, Nag-In Kim, *Member, IEEE*, Byung-il Kang, and Min-seok Hong

***Abstract*—This paper shows several structures of the hybrid excavator with the supercapacitor and compares them with each other from the aspect of fuel efficiency, the additional cost due to the hybridization, and the expected payback time. According to the comparison result, it can be concluded that a compound-type hybrid structure is a better solution than others because of its short expected payback time and higher reliability. In addition, the power control algorithm of the engine and the supercapacitor is proposed. To verify the proposed algorithm, the computer simulation and the engine dynamo test were performed, and the results are presented. The results show that the proposed control algorithm can achieve balance of the power and the energy between the energy sources and the load, and by hybridization, the fuel consumption can be reduced by about 24% compared with the conventional hydraulic excavator. The hardware implementation is now in progress for a 22-ton class excavator.**

***Index Terms*—Hybrid excavator, power control, supercapacitor.**

I. Introduction

THE COST of the energy has increased very rapidly, and pollution and global warming have become extremely serious problems. Thus, the hybrid system, which means a system having at least two of the energy sources including a combustion engine, has widely been adapted to several applications like vehicles, ships, and cranes to improve the fuel economy and the emission characteristics of their engines [1]–[7]. On the other hand, a hydraulic excavator, which is most widely used among the construction machinery, can be one of the best candidates for hybrid application because it consumes a large amount of energy, whereas its efficiency from fuel to actuator is less than 30%, and it emits lots of pollutants like nitrogen oxides and particle materials. As shown in Fig. 1, the conventional hydraulic excavator consists of four parts: 1) the engine; 2) the hydraulic pump; 3) the control valve (C/V); and 4) the hydraulic actuators. The mechanical power generated by the engine is converted to hydraulic power by the hydraulic pump. This hydraulic power is divided by the control valve to the corresponding actuators, which convert this hydraulic power to mechanical power.

One of the main reasons why the hybrid excavator can improve the fuel economy and reduce the emission is that the conventional hydraulic excavator cannot operate its engine in a high-efficiency region. In the conventional excavator system, the operating point of its engine should follow the power required by the load, which varies widely when the excavator works. The engine is operated around its maximum speed to avoid a sluggish transition from a light load operation of the excavator to a heavy load operation by keeping the hydraulic pressure. However, in the hybrid excavator, an energy storage device like a battery can be used as an energy buffer, and the electric motor can assist the engine in the heavy load operation. Thus, the engine can more efficiently be operated than the conventional excavator system. Another possibility that can improve the fuel consumption is the recuperation of the regenerative power. During the swing and boom motion in Fig. 1(b), there should be regenerative power, which is dissipated as heat in the conventional hydraulic excavator. However, in the hybrid excavator, this power may charge the energy buffer and can be reused for another operation.

Many research efforts on the structure of the hybrid excavator have been undertaken, and most of them use batteries for their energy buffer [8]–[10]. A supercapacitor can be used as the energy buffer instead of the battery [11]–[13]. As an energy storage device, it shows higher power density and lower energy density than the battery. For excavator application, because the load power of the engine fluctuates very fast and widely, a large capacity of the peak power is required for energy storage. Thus, the total weight of the energy storage device, which meets the requirement of the power capacity, can be reduced by using the supercapacitor instead of the battery. In addition, the charging and discharging efficiency of the supercapacitor is superior to that of the battery, and the price of the supercapacitor has drastically been reduced in the past decade due to the development of the manufacturing process. Therefore, the supercapacitor can be a promising candidate for the energy storage device of the hybrid excavator.

In this paper, several structures of the hybrid excavator with the supercapacitor are compared from the aspect of fuel efficiency, the additional cost due to the hybridization, and the

Manuscript received September 1, 2009; accepted October 9, 2009. Date of publication May 17, 2010; date of current version July 21, 2010. Paper 2009-IDC-300, presented at the 2008 Industry Applications Society Annual Meeting, Edmonton, AB, Canada, October 5–9, and approved for publication in the IEEE Transactions on Industry Applications by the Industrial Drives Committee of the IEEE Industry Applications Society.

T.-S. Kwon was with Seoul National University, Seoul 151-744, Korea. He is now with Hyundai MOBIS Company, Seoul 135-977, Korea (e-mail: sulsk@plaza.snu.ac.kr).

S.-W. Lee was with Seoul National University, Seoul 151-744, Korea. He is now with the Automation R&D Center, LS Industrial Systems Company, Anyang 431-080, Korea.

S.-K. Sul is with the School of Electrical Engineering, Seoul National University, Seoul 151-744, Korea.

C.-G. Park, N.-I. Kim, B. Kang, and M. Hong are with the Institute of Technology, Doosan Infracore Company, Ltd., Yongin 448-795, Korea (e-mail: Cheolgyu.park@doosan.com).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TIA.2010.2049815

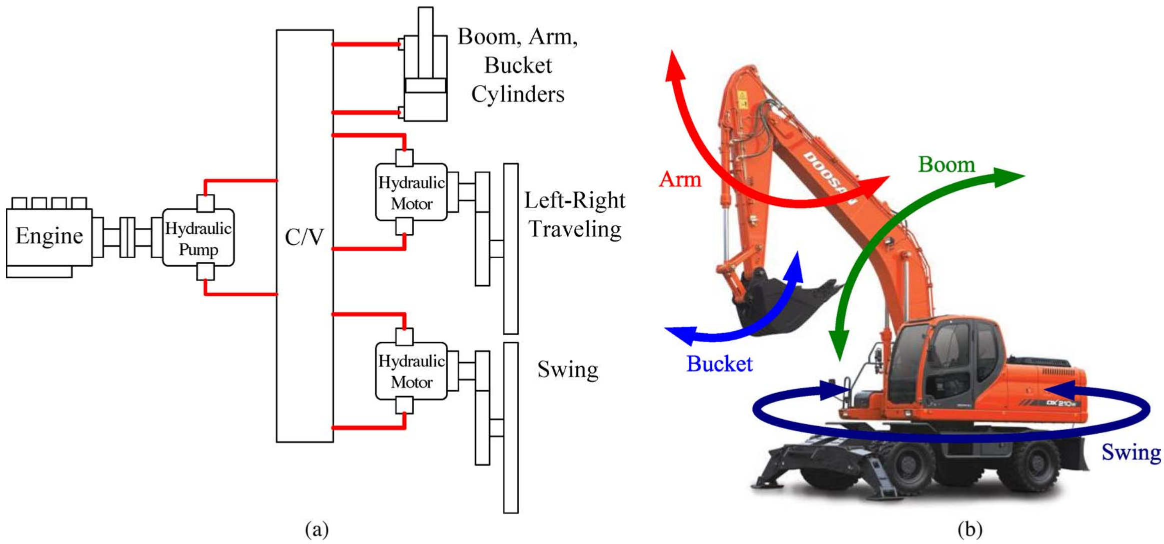


Fig. 1. (a) Structure and (b) operation of a conventionally hydraulic excavator.

expected payback time. According to the comparison result, the authors conclude that a compound-type hybrid structure is a better solution than others because of its short expected payback time and reliability. In addition, the power control algorithm of the engine and the supercapacitor is proposed. To verify the proposed algorithm, computer simulation was performed, and the results are presented. The hardware implementation is now in progress for a 22-ton class excavator.

II. Structures of the Hybrid Excavator and Comparison

Fig. 2 shows several structures of the hybrid excavator. In the series-type hybrid excavator in Fig. 2(a), all of the power generated by the engine is converted to electric power by the generator, and again, this electric power is converted to mechanical power by the electric motors to drive the hydraulic pumps. The swing actuator is replaced by the electric motor; hence, the recuperation of regenerative power is possible. Moreover, since the hydraulic line of the boom actuator is separated, the regenerative power of the boom actuator can be recuperated if a specific control valve is installed. The supercapacitor is charged when the load power is light or the swing motor and the boom actuator are operated in regenerative mode, and it is discharged when the load power is heavy. The engine in this structure can be operated at a more efficient operating point regardless of the operating point that is governed by the load since the engine is mechanically and hydraulically disconnected to the load. In addition, the hydraulic pump is divided into two parts in this figure to reduce the hydraulic loss in the hydraulic control valve. Unlike the hydraulic pump in the conventional excavator in Fig. 1(a), in this structure, the hydraulic pump is operated only when the corresponding actuator needs to operate; thus, the loss in the hydraulic control valve can be reduced. However, because all of the power that each hydraulic actuator requires should be supplied by the electric motors and their associated power electronics, and the generator should have almost the same capacity of the engine, the electrical devices are more massive than that of the other structures. Moreover, the power train, including the hydraulic devices, should be modified severely from the conventional one. Thus, this structure could have severe cost penalty.

On the other hand, in the parallel-type hybrid excavator in Fig. 2(b), the engine and the actuators are directly connected to each other by the mechanical shaft or the hydraulic line. Thus, the speed of the engine depends on the speed that the hydraulic pump requires, and only the torque of the engine can be modified from the required point by the amount of torque that comes from the generator. In addition, the recuperation of the regenerative power at the swing actuator is impossible. Thus, in the parallel type, less improvement of fuel economy is expected than in the series type. However, the generator does not need to have the same capacity as of the engine, so it can be designed smaller than that in the series type. Moreover, the modification of the power train and the hydraulic line can be minimized because of its simple structure. Hence, the additional cost for the hybridization is much less than that of the series type.

As mentioned before, in the parallel-type hybrid excavator, the regenerative power that might be generated in the swing motion is dissipated as heat by the hydraulic actuator and cannot be reused. To improve the fuel efficiency by using this regenerative power, the electrical motor can replace the hydraulic actuator for the swing motion, as shown in Fig. 2(c). This structure, which is called the compound-type hybrid excavator, has both of the advantages of the simple structure that comes from the parallel type and the usage of regenerative power that comes from the series type. Moreover, the hydraulic loss can be reduced a little by separating the swing motion from the hydraulic line. Table I shows the qualitative comparison of the fuel improvement characteristics between the above three structures.

A. *Comparison of the Fuel Consumption*

To compare them quantitatively, the fuel consumption is estimated by simulation using the load power profile shown in Fig. 3(a). The load profile is obtained from the real 22-ton class excavator when it is operated in the typical digging and

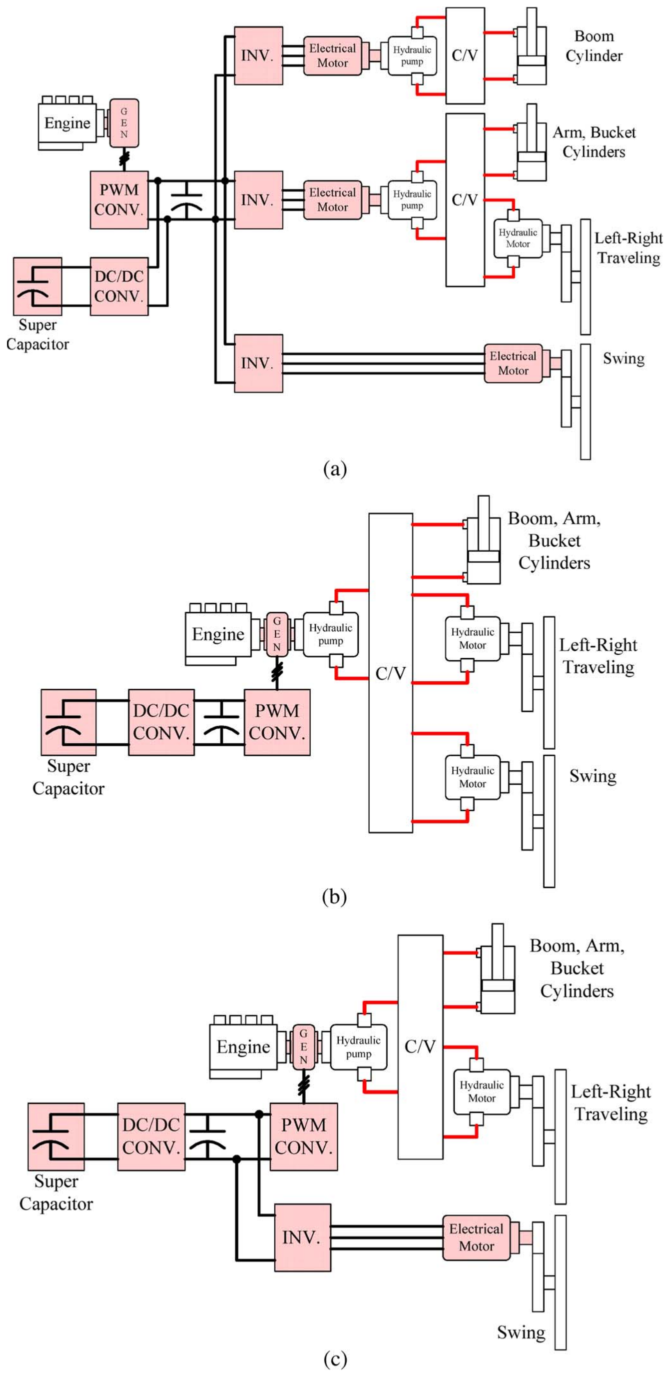


Fig. 2. Structures of the hybrid excavator. (a) Series type. (b) Parallel type. (c) Compound type.

TABLE I
COMPARISON OF FUEL IMPROVEMENT

	High efficient engine operation	Regenerative power Recovery	Reduction control valve loss
Series	○	○	○
Parallel	△	X	X
Compound	△	○	△

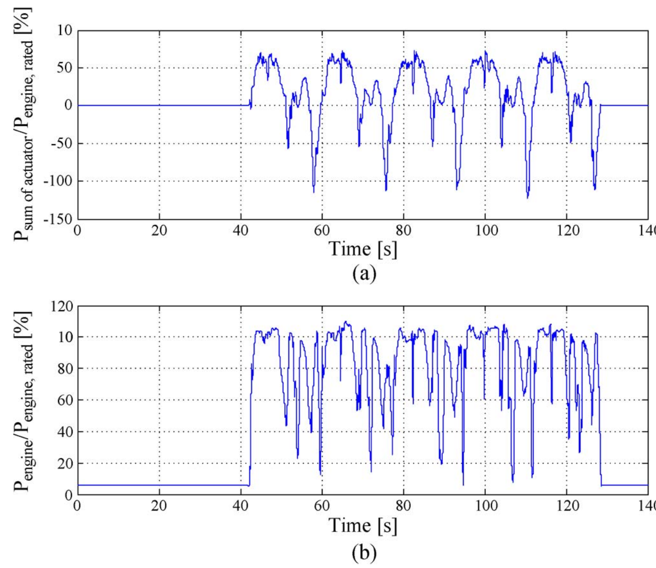


Fig. 3. (a) Sum of the actuator power and (b) engine power profile of the conventional excavator.

swing operation, so it consists of several cycles, including the series of various motions, for example, swing–boom–arm–bucket–arm–boom–swing–bucket, etc. Fig. 3(b) shows the actual output power of the conventional hydraulic excavator with the load power profile in Fig. 3(a). All the values in Fig. 3 are normalized by the rated engine power. In the simulation, the following assumptions are employed.

1) The efficiencies of the motors, the generators, the supercapacitor, and their power electronic devices are all 95%.
2) The efficiency of the gear box is 90%.
3) The efficiencies of the hydraulic pumps and the control valves are 85% and 70%, respectively.
4) The specific fuel consumption map is used for consideration of the engine efficiency.
5) The fuel cost is 1.5 USD per liter.

Fig. 4 shows the simulated engine power of each hybrid structure under the above assumptions. It can be known that the amount of engine power is getting reduced for the same load power profile from top to bottom, that is, from the parallel to the series type. The difference of the engine power between the conventional excavator and the hybrid ones corresponds to the supercapacitor power. If this difference is positive, then the surplus power is charged at the supercapacitor, and if the difference is negative, then the shortage is supplied from the supercapacitor. In the parallel-type hybrid system, any regenerative energy cannot be recuperated; thus, the amount of reduced engine power is not much. However, in the compound-type system, the regenerative power from the swing motion can be recovered, so the engine power can be reduced more than in the parallel type. In the series type, the regenerative power from the boom motion can also be recuperated, and the hydraulic loss of the control valve can be reduced; thus, the amount of reduced engine power is the largest.

Fig. 5 shows the comparison result of the fuel consumption with the load power profile shown in Fig. 3. All of the value is normalized with the fuel consumption of the conventional excavator. As expected, the series-type hybrid system shows

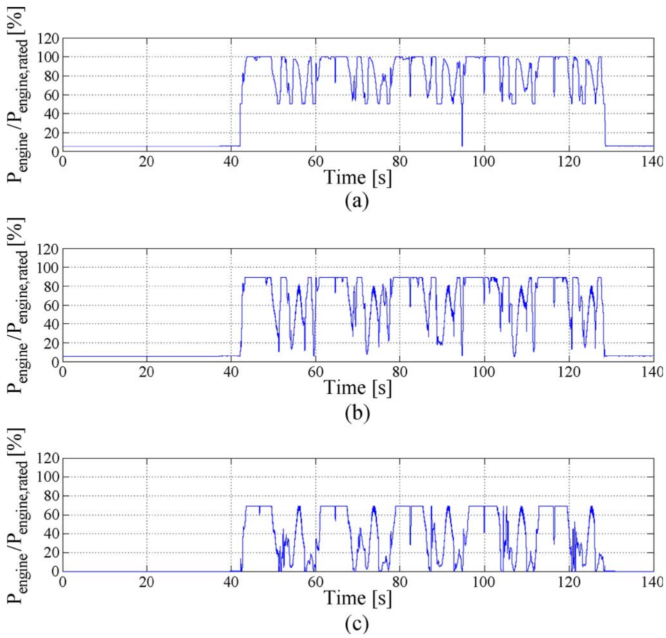


Fig. 4. Engine power profile of (a) the parallel-type, (b) the compound-type, and (c) the series-type hybrid excavator.

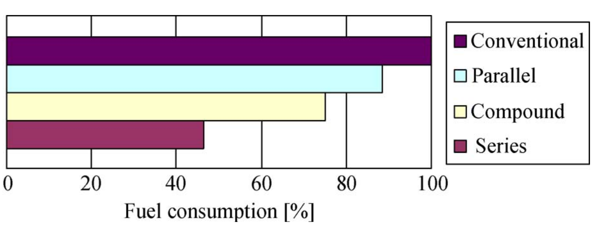


Fig. 5. Comparison of the fuel consumption with respect to that of the conventional excavator.

the lowest fuel consumption, which is about 45% of the fuel consumption of the conventional excavator.

B. Comparison of the Additional Cost

According to the analysis from the previous chapter, the series-type hybrid excavator is the most promising solution from the aspect of fuel efficiency. However, for the series-type hybrid excavator, a high cost should be paid for the hybridization. The capacity of the generator and its power converter should be large enough to cover the whole power range of the engine since all of the mechanical power should be converted to electrical power. In addition, a relatively large number of the motors and their power converter are required because to reduce the loss of the hydraulic line, each actuator should have its own hydraulic pump and control valve. Moreover, to achieve this loss reduction, the design of the hydraulic system is drastically changed, and additional hydraulic units are needed. To recover all of the regenerative power, the capacity of the supercapacitor should also be larger than that of the other structures.

On the other hand, for the parallel-type hybrid excavator, the capacity of the generator and its power converter is much less than that of the engine. Since the generative power is dissipated in the hydraulic line as a loss, the capacity of the supercapacitor is also less than the other structures. Moreover, an only minor

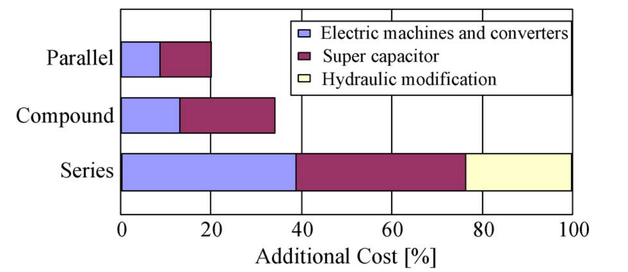


Fig. 6. Comparison of the additional cost with respect to that of the series-type hybrid excavator.

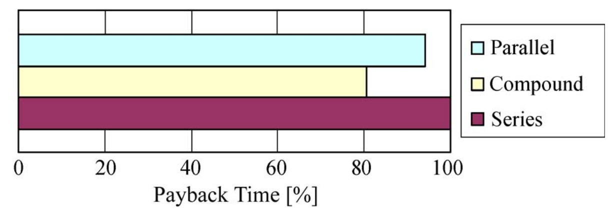


Fig. 7. Comparison of the payback time with respect to that of the series-type hybrid excavator.

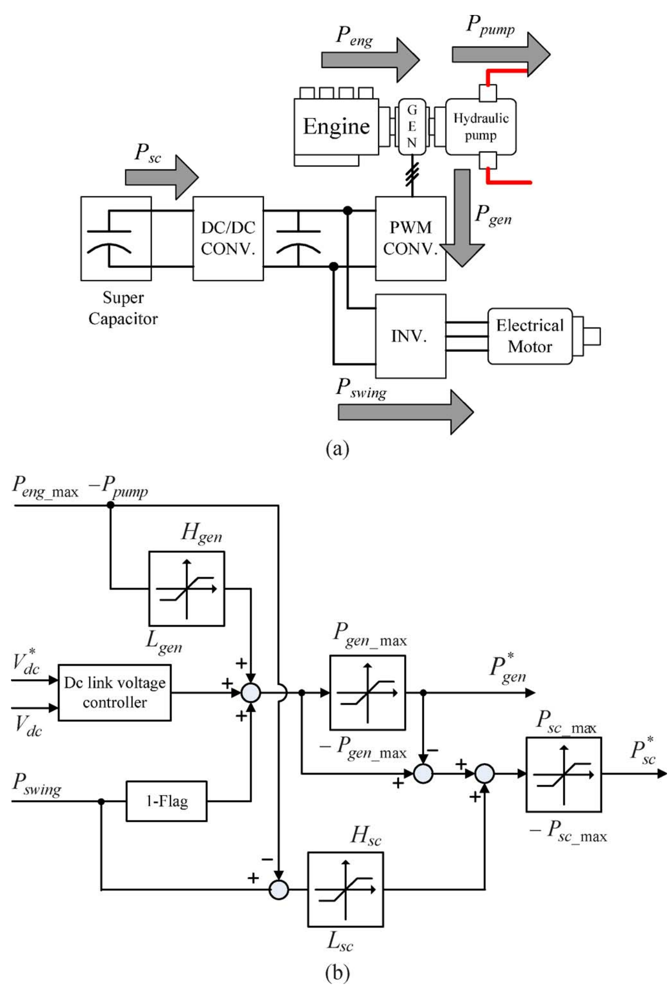


Fig. 8. (a) Notation of the power directions. (b) Block diagram of the power controller.

modification of the hydraulic system is required; thus, the cost for this modification would be neglected.

Fig. 6 shows the comparison result of the additional cost for composing each hybrid system. All of the value is normalized

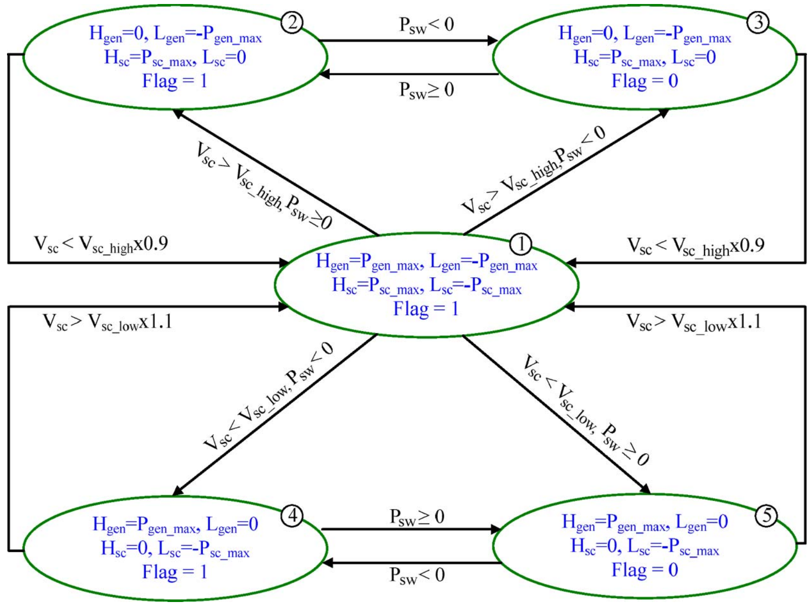


Fig. 9. State flowchart for the decision of the power commands of the generator and the supercapacitor.

with the cost for the series hybrid system. As expected, the series-type hybrid system requires a high cost, which is about 500% higher than that of the parallel-type hybrid system.

The compound-type hybrid system shows moderate characteristic for the fuel economy and additional cost. About 25% reduction of the fuel consumption is expected compared with the conventional excavator. Although this value is almost half of that of the series-type hybrid system, the additional cost for the compound system is almost one-third of that for the series system. Fig. 7 shows this characteristic with payback time. Payback time means the time in which the fuel cost reduced by applying the hybrid system is equal to the additional cost for composing it. All the value in Fig. 7 is normalized by the payback time of the series hybrid system. The saved fuel cost is obtained under the assumption that the operation time is 2000 h/year; during 30% of the operation time, the excavator is idling, and for the rest of the time, the excavator is continuously repeating the work shown in Fig. 3.

As shown in Fig. 7, although the series hybrid shows the largest fuel reduction, it presents the longest payback time. It is because the cost of the electrical machines and their converters is still high, and if their price goes down in the future, then the results would be totally different. Hence, the best candidate structure, right now, is the compound-type hybrid system from the aspect of the economical reason, as shown in Fig. 7. In addition to this point, the compound type and the parallel type can be considered as more reliable than the series-type excavator. In the series type, all the power flows through the electric path; thus, if failure to keep the dc-link voltage occurs, then the total system would stop. However, in the compound and parallel types, both electric and mechanical paths can be used for the power flow, and if one of them is to fail, then the total system can still be operated with unavoidable degraded performance. Thus, considering the economical point and the reliability, it can be concluded that the compound-type hybrid excavator is the best solution.

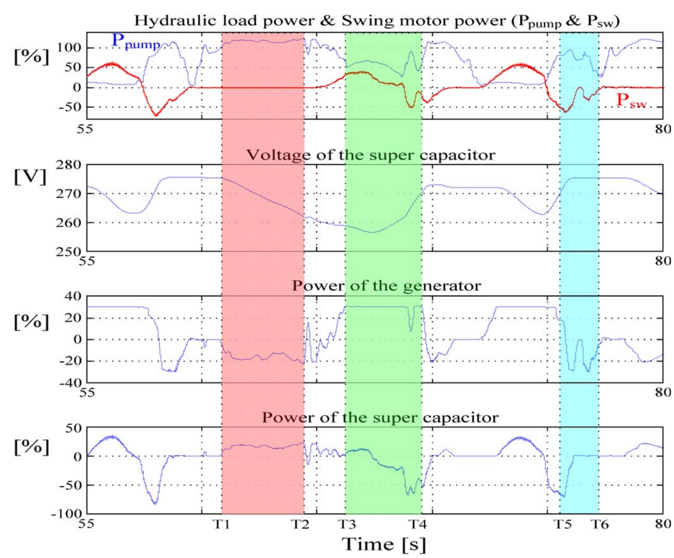


Fig. 10. Simulation result of the compound hybrid controller with the proposed power control strategy.

III. Power Control Strategy

Fig. 8 shows the block diagram of the power controller of the compound-type hybrid excavator. The power controller should provide a balance of the instantaneous power among the engine, the supercapacitor, and the load. It should also provide a balance of the supercapacitor energy during a period of a work.

As shown in Fig. 8, the power balance is achieved by the dc-link voltage control of the pulse width modulation converter, that is, the generator controls the dc-link voltage to a constant value in a feedback manner, and the energy balance is obtained by maintaining the supercapacitor voltage to a certain range in a feedforward manner, whereas the engine controls its speed to a nearly constant speed [4]. The swing power is supplied by the supercapacitor or the generator according to the value of the Flag. In Fig. 8, H_{sc} and L_{sc} are the upper and lower

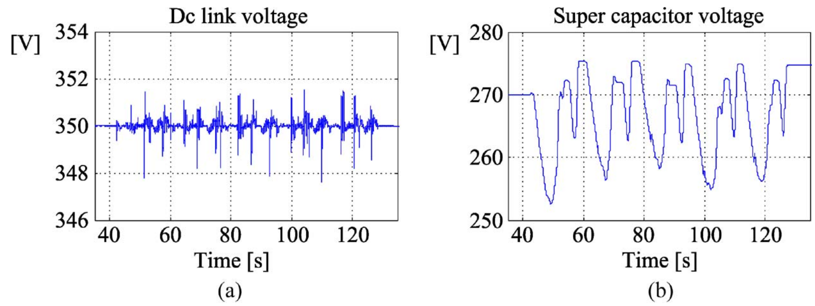


Fig. 11. Simulation result of the compound hybrid controller. (a) DC link voltage. (b) Supercapacitor voltage.

limit values of the power command of the supercapacitor, respectively. Similarly, H_{gen} and L_{gen} denote the upper and lower limit values of the power command of the generator. These values are decided considering the maximum efficiency engine power $P_{\mathrm{eng\_max}}$, the power requested by the hydraulic pump P_{Pump}, and the voltage of the supercapacitor V_{sc} using the state flowchart in Fig. 9. It is notable that $P_{\mathrm{eng\_max}}$ does not mean the maximum engine power in the whole operating region of the engine, instead of that it means the engine power that shows the maximum efficiency at the speed where the engine is operated. When the voltage of the supercapacitor is in the range between its higher limit $V_{\mathrm{sc\_high}}$ and its lower limit $V_{\mathrm{sc\_low}}$; the operating state corresponds to state 1. In this state, the supercapacitor could be discharged or charged according to $P_{\mathrm{eng\_max}} - P_{\mathrm{pump}}$. Hence, the limit values of the power commands of the generator and the supercapacitor are set to their maximum values. The swing power is supplied or absorbed by the supercapacitor in this state, thus "Flag" is set to 1.

If the voltage of the supercapacitor is larger than $V_{\mathrm{sc\_high}}$, then the supercapacitor cannot be charged; thus, the lower limit of the power command of the supercapacitor L_{sc} and the higher limit of the power command of the generator H_{gen} are set to 0. The swing power is supplied by the supercapacitor if it is positive; this corresponds to state 2, so "Flag" is set to 1. Otherwise (state 3), it is absorbed by the generator so the generator is operated in the motoring mode; thus, the regenerative power from the swing motion can share the power required by the hydraulic pump P_{Pump} with the engine. Although the voltage of the supercapacitor is higher than $V_{\mathrm{sc\_high}}$, the supercapacitor may be charged if the regenerative swing power is larger than the maximum power of the generator; thus, $V_{\mathrm{sc\_high}}$ should be selected considering the maximum regenerative power.

Fig. 10 shows the simulation result of the compound hybrid excavator at a certain moment with the power controller in Figs. 8 and 9. It is assumed that the excavator conducts the work described by the load profile in Fig. 3. From the top to the bottom in Fig. 10, it represents the power of the hydraulic load and the swing motor, the voltage of the supercapacitor, the power of the generator, and the power of the supercapacitor. The values of the power are normalized by the maximum efficiency engine power, and the higher limit voltage of the supercapacitor is set to 270 V. From T1 to T2, since the voltage of the supercapacitor is larger than its higher limit and the swing power is zero, this region corresponds to state 2. Therefore, the generator is operated in motoring mode, and the supercapacitor is discharged according to the difference between the hydraulic

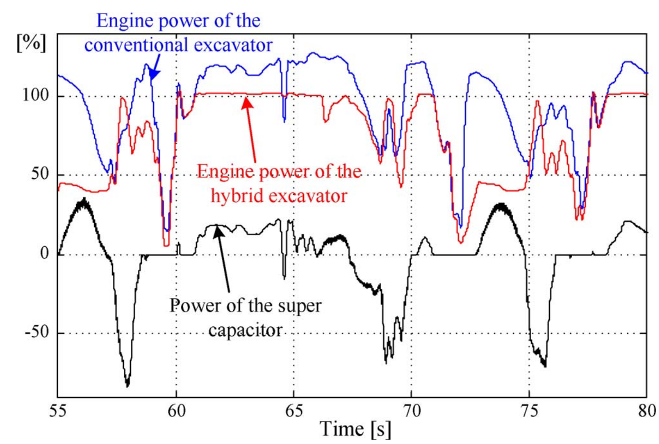


Fig. 12. Comparison of the engine power between the conventional excavator and the hybrid excavator with the supercapacitor.

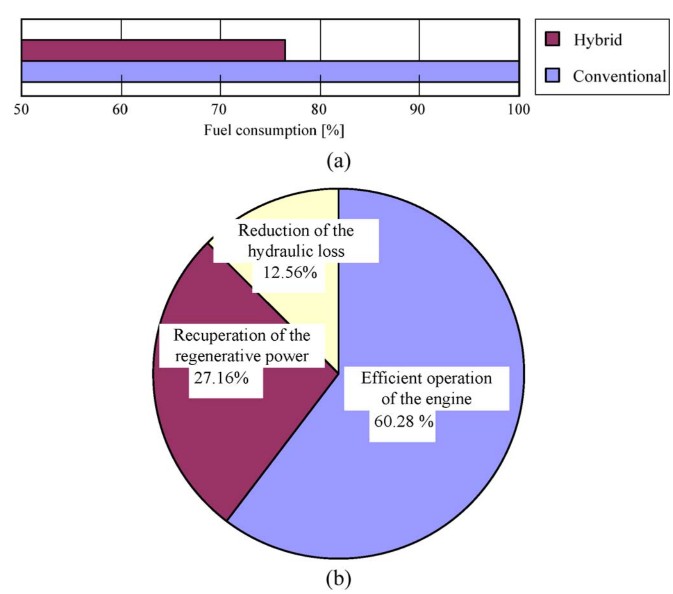


Fig. 13. (a) Comparison result of the fuel consumption and (b) pie chart of the reason of improvement.

load power and the engine maximum efficiency power. During T3–T4, the voltage of the supercapacitor is lower than its higher limit, so the rule of state 1 in Fig. 9 is applied. Thus, the swing power is supplied by the supercapacitor, and the generator tries to charge the supercapacitor. From T5 to T6, the voltage of the supercapacitor is larger than its higher limit, and the swing power is negative; thus, the state 4 in Fig. 9 decides

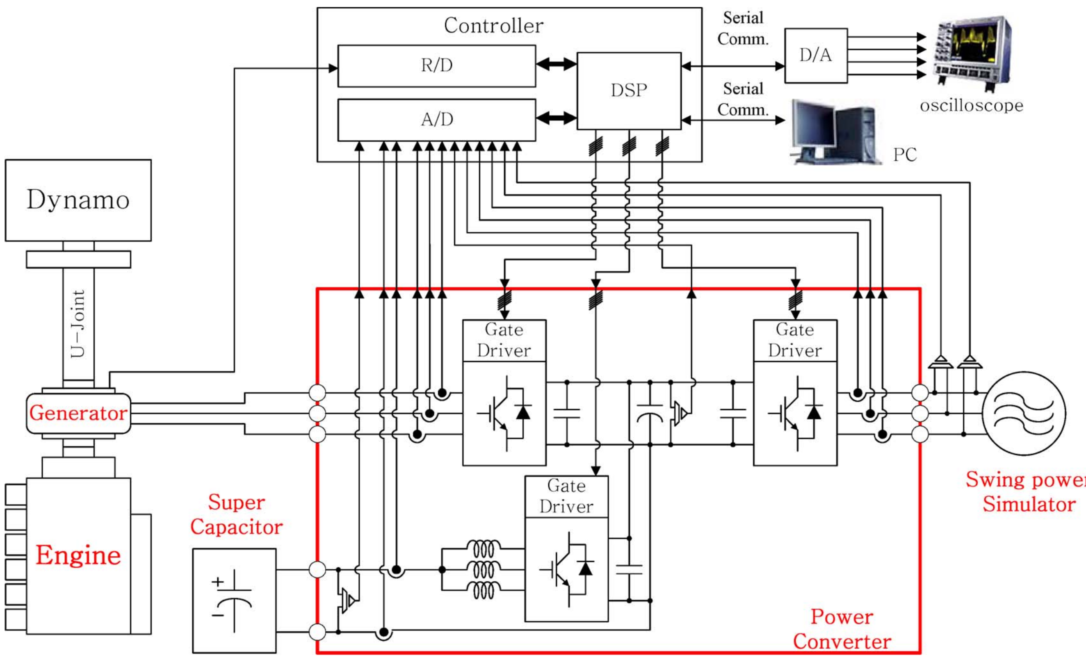


Fig. 14. Experimental setup for the engine dynamo test.

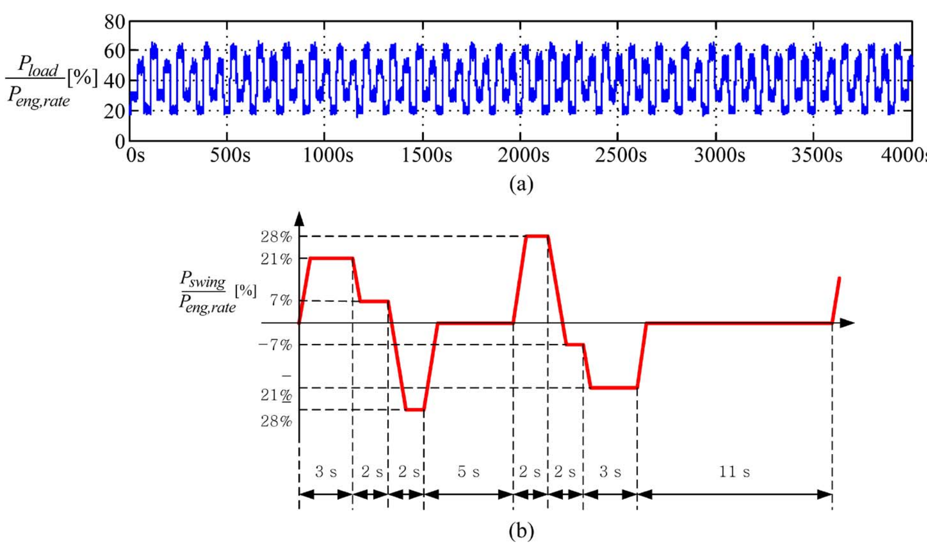


Fig. 15. (a) Profile of the load power for the dynamo meter and (b) simulated swing power.

the limit values of the power commands for the generator and the supercapacitor, and the regenerative swing power assists the engine through the generator.

Fig. 11 shows the dc-link voltage and the supercapacitor voltage during one work cycle of the excavator. It can be noticed that the balance of the instantaneous power among the engine, the supercapacitor, and the load is maintained, whereas the voltage of the supercapacitor is kept to a certain range during the cycle.

The comparison between the engine power of the conventional excavator and the hybrid excavator is shown in Fig. 12. It is obvious that the engine power of the hybrid excavator is lower than that of the conventional one. It is because the engine of the hybrid excavator shares the load with the supercapacitor power through the generator. Another reason is that in the hybrid excavator, the swing motor is not fed by the engine directly, instead of that it is fed by the supercapacitor; thus, the loss in the hydraulic line can be reduced, and the regenerative power of the swing machine can be recuperated.

Fig. 13 shows the comparison result between the fuel consumption of the hybrid excavator and the conventional one with the proposed power control strategy and the contributions of the reasons for fuel reduction. It can be known that the hybrid excavator could reduce the fuel consumption with the proposed power controller by about 24%, and the most of the improvement comes from the efficient operation of the engine.

IV. Experimental Results

To prove the power control strategy proposed in Section III, the engine dynamo test is performed. Fig. 14 presents the experimental setup, which shows the generator, which is directly

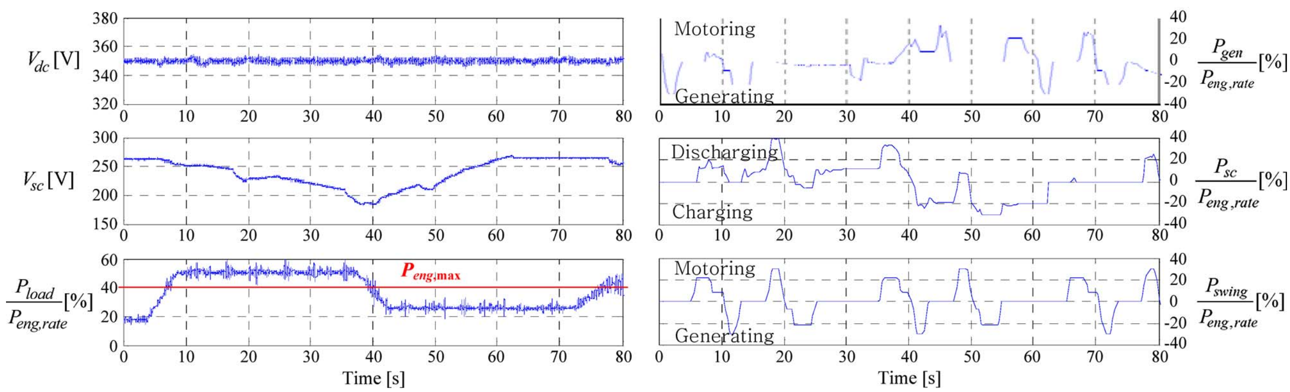


Fig. 16. Performance of the proposed power control strategy.

connected to the engine and the dynamo meter, the power converter, the supercapacitor, and the swing power simulator. The swing motion of the excavator is simulated in the power level by controlling the power from the power level. The load power profiles for the dynamo meter and the simulated swing power are shown in Fig. 15. All the values in Fig. 15 are normalized by the maximum efficiency engine power. Since the capacity of the dynamometer is not enough to cover the whole engine power, the tested load power is in the range between 20% and 60% of the maximum efficiency engine power, as shown in Fig. 15. Thus, 40% of the "real" maximum efficiency engine power is taken as $P_{\mathrm{eng\_max}}$ for the proposed power control strategy shown in Figs. 8 and 9.

Fig. 16 shows the performance of the proposed power control strategy. It can be shown that the dc-link voltage is well regulated in spite of the change of the load power and the swing power, and the voltage of the supercapacitor is kept in a certain range during the work cycle. This means that the proposed power controller achieves the instantaneous power balance and the energy balance during the work cycle.

To examine the effect on the fuel consumption, the load profile in Fig. 15(a) is applied without the simulated swing power. Since in the hydraulic excavator the swing power is supplied by the engine through the hydraulic line, whereas in the hybrid excavator it is supplied through the electrical line, the simulated swing power is not applied for this comparison to compare more fairly. As a result, the authors obtain 8% fuel reduction, whereas 24% fuel saving is expected in Section III. It is because in these experiments, the load power level is too low compared with the maximum efficiency engine power and the regeneration power, and the idling state is omitted.

V. Conclusion

In this paper, several structures of the hybrid excavator with the supercapacitor have been compared from the aspect of fuel efficiency, the additional cost due to the hybridization, and the expected payback time. From the comparison result, it can be concluded that a compound-type hybrid structure is the best solution among them because of its shortest expected payback time. In addition, the power control algorithm of the engine and the supercapacitor is proposed. To verify the proposed algorithm, computer simulation and experiments using engine dynamo set were performed, and the results are presented.

From the result, it can be known that the proposed power controller can keep the balance of the instantaneous power and the energy of the supercapacitor. Moreover, about 24% of the reduction of the fuel consumption with this controller is expected, and 8% fuel reduction can be obtained by the engine dynamo test. The reason for this difference between these results is that, due to the limitation of the dynamo setup, the load power level is too low compared with the maximum efficiency engine power and the regeneration power, and the idling state is omitted. The implementation of the prototype 22-ton class hybrid excavator is in progress to show the feasibility of the proposed controller and system.

References

[1] J. M. Miller, "Hybrid electric vehicle propulsion system architectures of the e-CVT type," *IEEE Trans. Power Electron.*, vol. 21, no. 3, pp. 756–767, May 2006.

[2] C. C. Chan, "The state of the art of electric vehicles technology," *Proc. IEEE*, vol. 90, no. 2, pp. 247–275, Feb. 2002.

[3] A. Emadi, K. Rajashekara, S. S. Williamson, and S. M. Lukic, "Topological overview of hybrid electric and fuel cell vehicular power system architectures and configurations," *IEEE Trans. Veh. Technol.*, vol. 54, no. 3, pp. 763–770, May 2005.

[4] S.-M. Kim and S.-K. Sul, "Control of the rubber tyred gantry crane with energy storage based on super capacitor bank," *IEEE Trans. Power Electron.*, vol. 21, no. 5, pp. 1420–1427, Sep. 2006.

[5] D. H. Clayton, S. D. Sudhoff, and G. F. Grater, "Electric ship drive and power system," in *Conf. Rec. 24th Int. Power Modular Symp.*, Jun. 2000, pp. 85–88.

[6] A. Monti, D. Boroyevich, and D. Cartes, "Ship power system control: A technology assessment," in *Proc. IEEE Elect. Ship Technol. Symp.*, Jul. 2005, pp. 292–297.

[7] S.-Y. Kim, Y.-D. Yoon, and S.-K. Sul, "Suppression of the thrust loss for the maximum thrust operation in the electric propulsion ship," in *Proc. IEEE Elect. Ship Technol. Symp.*, May 2007, pp. 72–76.

[8] H. Yoshimatsu, "Driving device of working machine," Japan Patent 2001-12274, Jan. 16, 2001.

[9] Q. Xiao, Q. Wang, and Y. Zhang, "Control strategies of power system in hybrid hydraulic excavator," *Autom. Construct.*, vol. 17, no. 4, pp. 361–367, May 2008. [Online]. Available: http: //www.elsevier.com/locate/autcon/

[10] M. Kagoshima, T. Sora, and M. Komiyama, "Hybrid construction equipment power control apparatus," U.S. Patent 7 069 673, Jul. 4, 2006.

[11] E. J. Cegnar, H. L. Hess, and B. K. Johnson, "A purely ultracapacitor energy storage system hybrid electric vehicles utilizing a based DC–DC boost converter," in *Proc. IEEE Appl. Power Electron. Conf. Expo.*, May 2004, vol. 2, pp. 1160–1164.

[12] B. Maher, *Ultracapacitors and Hybrid Vehicle*. [Online]. Available: http://www.maxwell.com/pdf/uc/white-apers /utracapacitors_and_hevs.pdf

[13] J. M. Miller and M. Everett, "An assessment of ultra-capacitors as the power cache in Toyota THS-II, GM-Allision AHS-2 and Ford FHS hybrid propulsion systems," in *Proc. IEEE Appl. Power Electron. Conf. Expo.*, Mar. 2005, vol. 1, pp. 481–490.

Tae-Suk Kwon (S'04–M'08) was born in Seoul, Korea, in 1973. He received the B.S. and M.S. degrees in electrical engineering from Hanyang University, Seoul, in 1995 and 1997, respectively, and the Ph.D. degree in electrical engineering from Seoul National University, Seoul, in 2007.

From 1997 to 2003, he was a Research Engineer with Hyundai Elevator Company Technical R&D Center, Ichon, Korea, where he developed high-speed gearless elevator systems. Since 2008, he has been a Principal Engineer with Hyundai MOBIS Company, Seoul. His interests include high-performance ac drive systems and hybrid electric vehicle drives.

Seon-Woo Lee was born in Korea in 1982. He received the B.S. degree in electronic and electrical engineering from Hanyang University, Seoul, Korea, in 2006, and the M.S. degree in electrical engineering and computer science from Seoul National University, Seoul, in 2008.

Since 2008, he has been a Research Engineer with the Automation R&D Center, LS Industrial Systems Company, Anyang, Korea. His current research project is the development of the 100-kVA IGBT inverter for high-speed electric vehicles.

Seung-Ki Sul (S'78–M'80–SM'98–F'00) was born in Korea in 1958. He received the B.S., M.S., and Ph.D. degrees in electrical engineering from Seoul National University, Seoul, Korea, in 1980, 1983, and 1986, respectively.

From 1986 to 1988, he was an Associate Researcher in the Department of Electrical and Computer Engineering, University of Wisconsin, Madison. From 1988 to 1990, he was a Principal Research Engineer with Gold-Star Industrial Systems Company. Since 1991, he has been a member of the faculty of the School of Electrical Engineering, Seoul National University, where he is currently a Professor. His current research interests are power electronic control of electric machines, electric/hybrid vehicle drives, and power-converter circuits.

Cheol-Gyu Park was born in Korea in 1969. He received the B.S., M.S., and Ph.D. degrees in mechanical design and production engineering from Seoul National University, Seoul, Korea, in 1991, 1993, and 1999, respectively.

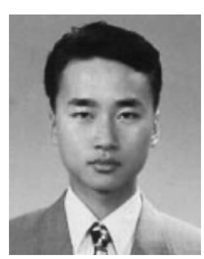
Since 1999, he has been with the Institute of Technology, Doosan Infracore Company, Ltd., Yongin, Korea, where he is currently a Principal Researcher. His application areas are modeling of hydraulic systems, control of dynamic systems, and hybrid power train systems for construction equipment.

Nag-In Kim (S'85–M'87) was born in Korea in 1962. He received the B.S. degree in mechanical engineering from Korea Aviation University, Goyang, Korea, and the M.S. and Ph.D. degrees in mechanical engineering from the Korea Advanced Institute of Science and Technology, Daejeon, Korea.

Since 1987, he has been with the Institute of Technology, Doosan Infracore Company, Ltd., Yongin, Korea, where he is currently Managing Director. His current interests include technology planning of the corporation and eco-technologies, such as hybrid vehicle and low-temperature combustion of diesel engine.

Byung-il Kang was born in Korea in 1975. He received the B.S. and M.S., degrees in mechanical engineering from Korea University, Seoul, Korea, in 1998 and 2000, respectively.

In 2000, he joined Doosan Infracore, Yongin, Korea, where he is currently a Senior Research Engineer. His application areas are simulation, design, and test of hydraulic systems. His current research interests include hydraulic systems for increasing the efficiency of hybrid power train systems for construction equipment.



Min-seok Hong was born in Korea in 1971. He received the B.S. degree in electrical engineering from Myongji University, Korea, in 1995.

Since 1995, he has been with the Institute of Technology, Doosan Infracore, Yongin, Korea, where he is currently a Senior Researcher. His current research interests include power electronics and ac motor control.