Adaptive Design Validation of IPMSG for Superior EPGS of RE-EV compatible to Main Operating Range via Optimal Operating Line

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Numerical design and validation combined with Finite Element Method (FEM) has been performed for realizing the adaptive efficiency distribution and expanded continuous rated power of Interior Permanent Magnet Synchronous Generator (IPMSG) with a built in engine compatible to the mainly frequent operating range for Electric Power Generating System (EPGS) of Range Extended Electric Vehicle (RE-EV). Particularly, the target operating region of IPMSG is specified with Optimal Operating Line (OOL) of the newly developed two cylinders engine. The dominant electromagnetic losses throughout the whole operating region of IPMSG are numerically identified in association with FEM and employed as design target to minimize. In addition, the compact IPMSG is modeled with taken into the advanced cooling structure and MTPA (Maximum Torque Per Ampere) control strategy. Furthermore, the purposely designed prototype is experimentally validated via the resultant efficiency map built-up by the static and dynamic dynamometer tests.

***Index Terms*—Finite Element Method (FEM), Interior Permanent Magnet Synchronous Generator (IPMSG), Electric Power Generating System (EPGS), Range Extended Electric Vehicle (RE-EV), Optimal Operating Line (OOL).**

I. INTRODUCTION

DEVELOPMENT of green car is dramatically accelerated to deal with the environmental regulation control and fossil fuel depletion dependent on fuel economy and hazardous emissions. However, Hybrid Electric Vehicle (HEV) and Electric Vehicle (EV) have disadvantage of high cost, battery weight and deficient total driving distance. Hence, RE-EV is getting the spotlight in the eco-friendly vehicle as one of the alternative candidates, which increase the energy storage capacity and extend the pure electric driving distance.

In particular, EPGS is mostly significant to fuel economy and total driving distance of RE-EV, which is composed of the electric generator mechanically coupled with engine system. For the sake of RE-EV's running fulfillments, EPGS is utilized to charge the high voltage battery in accordance with the required electric power. IPMSG characterized with the superiority of high efficiency and torque density takes center stage as an electric generator of EPGS in that fuel efficiency of RE-EV is directly linked with efficiency characteristics of IPMSG. Continuous rated power and efficiency distribution of IPMSG should be improved for superior EPGS of RE-EV [1].

In addition, it is mandatory for EPGS of RE-EV to employ on OOL which comes from the best efficiency points of engine and IPMSG at each operating speed. Hence, OOL of EPGS should be obtained to advance the efficiency for the specified operating range of IPMSG, which can be achieved through the numerical and experimental design validation of IPMSG compatible to the engine characteristics.

In this paper, numerical design based on FEM coupled with MTPA has been performed for realizing the advanced efficiency range and extended continuous rated power region for the specialized IPMSG of EPGS compatible to the frequent operating range dependent on OOL [2].

In accordance, adaptive design process follows the two-steps; the first step is to obtain the possibly acceptable design result without taken into account the developed engine characteristics, and the second step is to refine the design parameters in detail aiming at the adaptive efficiency area and extended continuous rated power region for OOL of engine [3].

Furthermore, the purposely designed IPMSG for EPGS of RE-EV is experimentally evaluated under static and dynamic condition making use of dynamometer setup. In accordance, validness of the designed IPMSG is clarified with the measured efficiency map which shows good compatibility to the main operating range and OOL of EPGS [4].

II. NUMERICAL DESIGN OF IPMSG COMPATIBLE TO OOL

The major target operating range for design and validation based on the EPGS characteristics can be registered In Fig.1. Likewise, design specifications of the proposed IPMSG are summarized in Table I. At the first-step for Model I, we can obtain the possibly acceptable design result of overall structural dimension for IPMSG of EPGS even if the characteristic of the newly developed two cylinders type engine is unapplied for the design of IPMSG. At the second-step for Model II, design refinement of IPMSG for EPGS of RE-EV is performed to accomplish the adaptive efficiency and extended continuous rated power region [1].

TABLE I
DESIGN SPECIFICATIONS OF IPMSG FOR EPGS OF RE-EV

Section	Design Parameter	Specification		Unit
		Model I	Model II	
Performance	Rated Power	25	32	[kW]
	Rated Torque	68.3	90	[Nm]
	Rated Speed	3500	3500	[r/min]
General	No. of Pole/Slot	16 / 24	16 / 24	-
	No. of Phase	3	3	-
	Air-Gap	0.8	0.8	[mm]
Stator	Outer Diameter	280	280	[mm]
	Core Material	Silicon Steel	Silicon Steel	-
Rotor	Permanent Magnet	NdFeB	NdFeB	[T]

Model I: The first-step design, Model II: The second-step design

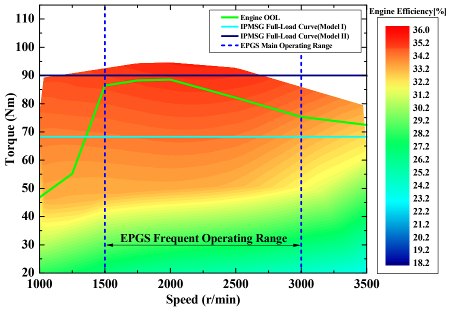
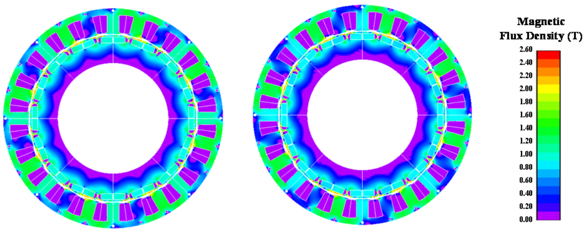


Fig. 1. Engine efficiency map and IPMSG Full-Load Curves (Model I and II).

In Fig. 1, the full load curves of IPMSG in engine efficiency map and main operating region are compared are between model I and II. It has been expected that model II has the better compatibility to high efficiency area of engine than model I in the frequent operating range of EPGS.

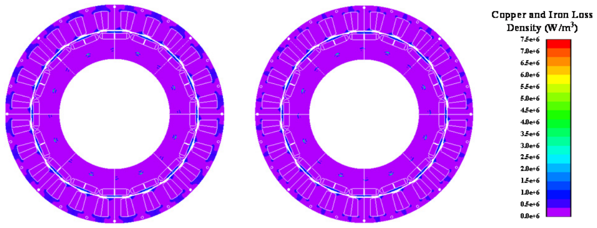
In particular, the proposed IPMSG based on FEM combine with MTPA control yielding [2], which is analyzed to minimize the copper loss. Additionally, the structural refinement of configuration is executed, which provides the minimized iron and PM loss via spatial harmonics reduction.

For reference, flux distributions of the numerically designed IPMSG on the lower and higher temperature condition for the improved second-step design are depicted in Fig. 2, of which corresponding copper and iron losses at the issued temperature are numerically computed and presented in Fig. 3 [3].



(a) 90 Nm@3,500 r/min (338.1 K) (b) 90 Nm@3,500 r/min (433.1 K)

Fig. 2. Comparison results of flux density distribution.



(a) 90 Nm@ 3,500r/min (338.1 K) (b) 90 Nm@3,500 r/min (433.1 K)

Fig. 3. Comparison results of numerically computed electromagnetic losses.

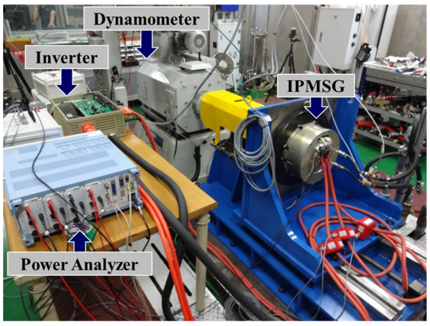


Fig. 4. Experiment-setup with dynamometer for measurement.

III. EXPERIMENTAL VALIDATION WITH DYNAMOMETER TEST

The experiment-layout with dynamometer is shown in Fig. 4, whereby static and dynamic characteristics for the purposely designed prototype are measured to verify the efficiency and continuous rated power performances [4].

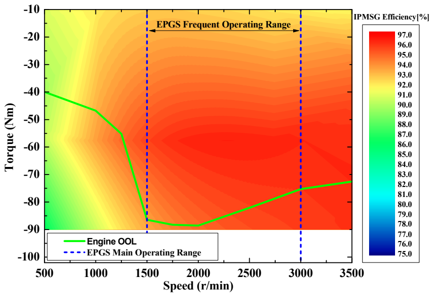


Fig. 5. Efficiency map for the purposely designed IPMSG.

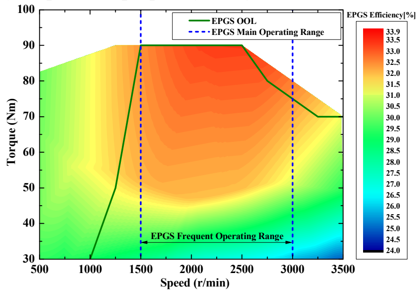


Fig. 6. Efficiency map and OOL for the purposely designed PMSG.

As it can be known in Fig. 5, the measured efficiency of IPMSG with the applied second-step design is distributed from 90.4% to 96.5% in frequent operating region of EPGS.

As indicated in Fig. 6, the measured efficiency range of EPGS with the purposely designed IPMSG is covering level of 30.3% to 33.1% in main operating region of EPGS, which shows good-efficiency compatible to OOL. As a result, it is found that the efficiency distribution for the advanced EPGS of RE-EV is obtained by the adaptive design and validation of IPMSG considering the main operating range via OOL.

IV. CONCLUSION

The purposely designed IPMSG in association with FEM and MTPA control strategies shows adaptive design results compatible to the frequent operating range which is identified for EPGS of RE-EV. Furthermore, the optimal operating line of EPGS is properly obtained through the experimental efficiency maps of engine and IPMSG.

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