http://dx.doi.org/10.11142/jicems.2012.1.4.1.419
Journal of International Conference on Electrical Machines and Systems vol. 1, no. 4, pp. 419~424 , 2012 ***419***

Percussive Drilling Application of a Tubular Reciprocating Translational Motion Permanent Magnet Synchronous Motor

Shujun Zhang*, Lars Norum*, Robert Nilssen* and Robert D. Lorenz**

Abstract - This paper presents a tubular reciprocating translational motion permanent magnet synchronous motor for percussive drilling applications for offshore oil & gas industry. The motor model and rock model are built up by doing force analysis of the motor and analyzing the physical procesof impact. The optimization of input voltage waveforms to maximize the rate of penetration is done by simulations. The simulation results show that the motor can be utilized in percussive drilling applications and achieve a very large impact force. Simulation results for optimization also show that second harmonic input voltage produces a higher rate of penetration than the sine wave and fourth harmonic input voltages.

Keywords: Permanent magnet motor, Tubular reciprocating translational motor, Percussive drilling, Rate of penetration, Hard rock drilling

1. Introduction

There is clear evidence that percussive drilling can sometimes increase the Rate of Penetration (ROP) in hard-rock formations. Percussive drilling (even without rotation) can often produce bigger ROP than conventional means such as rotary drilling or diamond drilling, especially in some hard-rock formations such as siliceous granite, sandstone, limestone, dolomite, etc. It has been demonstrated that in a medium-hard granite, with the same RPM and the weight on drill bit, the percussive-rotary method is 7.3 times faster than the conventional rotary method, while at the best operational conditions for both methods, percussive-rotary has a 2.3 times advantage in ROP [1],[2]. For the time being, there are two dominant driving methods in percussive drilling of down-the-hole (DHL) applications in the market: one is the pneumatic hammer, another is the hydraulic hammer or water powered hammer [3],[4]. The main disadvantage of pneumatic hammers is low energy utilization. A natural disadvantage of water powered hammers is the need for relatively large amounts of preferably high quality water to drive the hammer, occasionally leading to waste disposal problems. The water powered hammer also has another disadvantage of large pressure fluctuations in the feed water line caused by discontinuous consumption of water. This will decrease the reliability of the whole system. The DTH hammer driven by a tubular reciprocating translational motion permanent magnet synchronous motor (RTPMSM) [5] is a good option for overcoming the aforementioned problems. The RTPMSM will be working in oscillation mode. The huge impact force converted from the electric power source by the RTPMSM during the oscillations will be used to crush rock. The electric energy is directly transmitted to the hammer bit by the RTPMSM without any gears or other media. Therefore, the tubular RTPMSM can provide more efficient power transformation with higher reliability for the oil & gas industry under the high temperature and high pressure operating conditions than the existing solutions.

2. Tuburar Rtpmsm System and its Model

The system configuration in this work and its equivalent model are shown in Fig. 1 and Fig. 2, respectively. The tubular RTPMSM consists of an inner oscillatory subsystem and an outer oscillatory subsystem. The inner subsystem consists of a movable secondary with laminations of permanent magnets and iron, two gas springs inside of each end of the casing, and a viscous damper between the moving secondary and casing. The outer subsystem consists of a

---

* Department of Electric Power Engineering, Norwegian University of ScienceandTechnology,Norway(Shujun.Zhang@elkraft.ntnu.no, lars.norum@ntnu.no, robert.nilssen@elkraft.ntnu.no)
** Department of Mechanical Engineering, University of Wisconsin-Madison, USA (lorenz@engr.wisc.edu)
Received 03 July 2012 ; Accepted 05 October 2012

casing with a primary winding, an external spring connecting with the drill cylinder, and the viscous damper between the casing and drill cylinder. The alternating electromagnetic force is produced by the interaction between the permanent magnets and the primary winding carrying alternating current. This force drives the moving secondary back and forth in a forced resonant mode oscillation. The casing is driven by the reaction force from the inner subsystem. The casing impacts the hammer bit at its peak velocity when the moving secondary oscillates up and down. The hammer bit transfers all the impact energy from the casing to the rock. A top force F_T is needed at the top of drill cylinder in order to make the hammer bit contact the rock during the drilling process.

The following assumptions have also been made for the purpose of simplification before building up the mathematic model of the tubular RTPMSM:

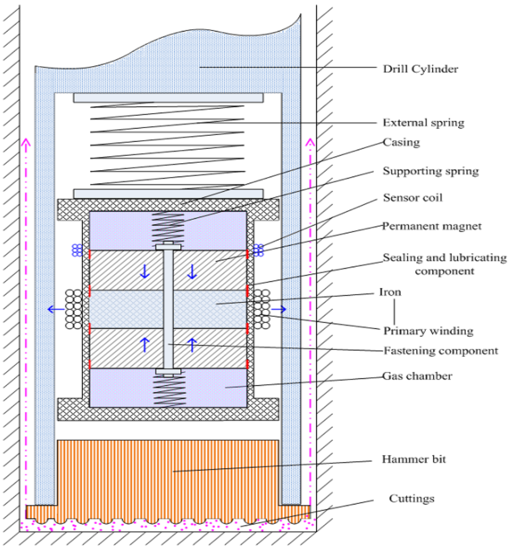

Fig. 1. Topology of DTH hammer driven by tubular RTPMSM

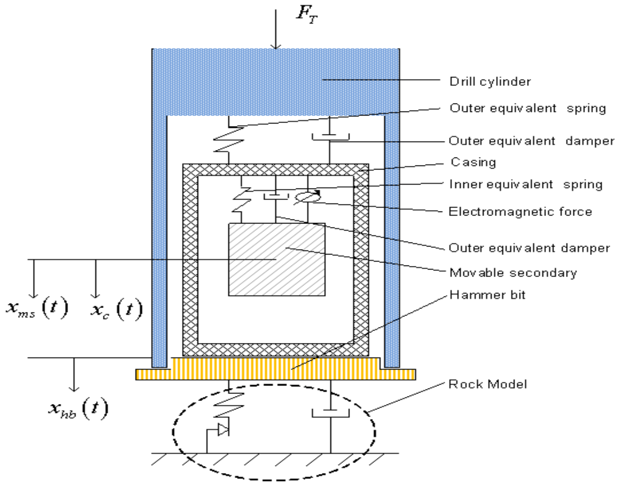

Fig. 2. Equivalent model of DHT hammer system

- No magnetic saturation;
- No fringing of the magnetic circuit;
- Eddy currents and hysteresis effects are neglected;
- No gas leakage between two gas chambers;
- Gravity force is neglected.

The force analysis for the moving secondary and casing is based on Newton's second law of motion. The mathematical model of the RTPMSM motion is described by (1) and (2) [6]:

$$m_{ms}\ddot{x}_{ms}(t) = f_{netIN}(t) = f_{em}(t) - K_{ie}\left[x_{ms}(t) - x_c(t)\right] - c_{ie}\left[\dot{x}_{ms}(t) - \dot{x}_c(t)\right] \quad (1)$$

$$m_c\ddot{x}_c(t) = f_{netIN}(t) - K_{oe}x_c(t) - c_{oe}\dot{x}_c(t) - d f_h(t)$$

$$d = \begin{cases} 1 & impact \\ 0 & no\ impact \end{cases} \quad (2)$$

where m_{ms} and m_c , $x_{ms}(t)$ and $x_c(t)$ are the mass and the displacement of the moving secondary and casing, respectively. K_{ie} and K_{oe}, c_{ie} and c_{oe} are the stiffness coefficients and viscous damping coefficients of the inner subsystem and outer subsystem, respectively. $f_{em}(t)$ is the electromagnetic force, $f_h(t)$ is the counter force on the casing from the hammer bit due to impacts.

The mathematical model of electrical and electromechanical parts of the tubular RTPMSM is described by (3), (4), (5) and (6):

$$v_d(t) = R_p i_d(t) + L_d \frac{di_d(t)}{dt} - \omega_e(t) L_q i_q(t) \quad (3)$$

$$v_q(t) = R_p i_q(t) + L_q \frac{di_q(t)}{dt} + \omega_e(t)\left[L_d i_d(t) + \lambda_{pm}\right] \quad (4)$$

$$\omega_e = n_p \omega_{ms}(t) = n_p \frac{\pi v_{ms-c}(t)}{\tau} \quad (5)$$

$$f_{em}(t) = \frac{3\pi}{2\tau} n_p \left[\lambda_d i_q(t) + \left(L_d - L_q\right) i_d(t) i_q(t)\right] \quad (6)$$

where R_p is the resistance of primary winding; $v_d(t)$ and $v_q(t)$, $i_d(t)$ and $i_q(t)$, L_d and L_q are voltage, current and inductance in d- and q-axis, respectively; $\omega_e(t)$, $\omega_{ms}(t)$ and $v_{ms\text{-}c}(t)$ are the electrical speed, mechanical speed and relative translational velocity of the moving secondary; τ is pole pitch; and n_p is the number of pole pairs.

3. Rock Model

A visco-elastic-plastic model of the rock is shown in Fig. 3[7]. The rock model consists of the mass of the hammer bit (m_{hb}), linear spring (K_r), viscous damper (c_r) and coulomb friction element with a threshold force (F_{thr}). The linear spring and viscous damper represent the visco-elastic nature of hard rock before fracture and the Coulomb friction element (F_{thr}) is the crushing threshold force of the rock medium. When a positive impact force ($f_h(t)$) is applied to the hammer bit, spring force ($f_{rs}(t)=K_r x_{hb}(t)$) builds up in the visco-elastic zone but no penetration movement of the hammer bit is achieved as long as the spring force ($f_{rs}(t)$) does not exceed the rock threshold force. When the spring force exceeds the threshold, the rock begins to fracture and the threshold friction element moves to emulate the rock, deforming plastically as the rock is crushed. During this plastic deformation of the rock, it is assumed that all cuttings are removed instantly from the crushed surface. It is also assumed that, when the net force of the linear spring exceeds F_{thr}, the threshold friction element instantly achieves the same velocity as the hammer bit.

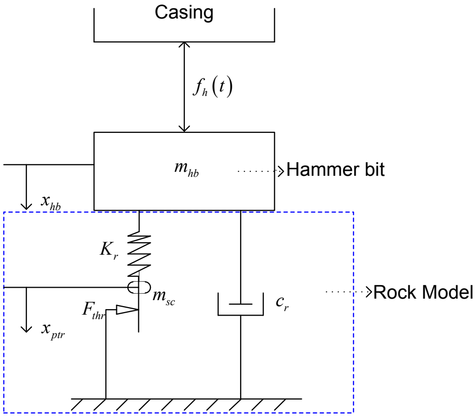

Fig. 3. Rock model

According to the amplitude of impact force, its expression in one impact cycle can be written as a piecewise function as follows in (7):

$$f_h(t)=\begin{cases} K_r x_c(t)+c_r\cdot\dot{x}_c(t) & \le K_r x_c(t)\le F_{thr} \\ F_{thr}+c_r\cdot\dot{x}_c(t) & K_r x_c(t)>F_{thr} \\ 0 & x_c(t)<0 \end{cases} \tag{7}$$

Different rocks have different stiffness coefficients of spring, viscous damping coefficient, and different threshold forces. The force and energy analysis for (7) is shown below:

- When the impact force is less than the threshold force, the impact force does not crush the rock and the rock behaves as a spring connected with a damper in parallel. A part of the impact energy dissipates in the viscous damper and the rest of the energy is returned to the system.
- When the impact force is bigger than the threshold force, the impact force crushes the rock. All of the kinetic energy of the casing is delivered to the rock. The bigger the impact force is; the higher the ROP is.
- When the casing moves up, there is no impact force.

The mathematic model of the whole system including rock model is thus given by (1)-(7).

4. Control Analysis

The first control objective for the tubular RTPMSM is to oscillate the casing in order to make the hammer bit crush the rock. The system is a mass-spring oscillatory system so that the trajectory of the driving force (electromagnetic force) should be a function of the alternating waveform and its frequency should be equal to the natural frequency of the oscillatory system. The natural frequency of the outer system is given by (8)

$$\omega_n=\sqrt{\frac{4m_c K_{oe}-2c_{oe}^2}{4m_c^2}}\approx\sqrt{\frac{K_{oe}}{m_c}} \tag{8}$$

(9)The second control objective for the system is to provide an impact force, which is high enough to crush the rock, i.e. the impact force produced by the casing should meet the following expression (9):

$$f_h(t)>F_{thr}+c_r\cdot\dot{x}_c(t) \tag{9}$$

For certain rock, the bigger the impact force is, the higher the ROP is. On the other hand, if we increase the impact force, the losses will be higher due to higher copper losses in the primary winding and the system efficiency will be lower. Therefore, a trade-off between the ROP and system efficiency exists in the real system.

The third objective is to optimize the input voltage in order to maximize the ROP and minimize the losses. Different input voltages with the same amount of energy input, such as cosine, rectangular, and harmonic waveforms can be used to supply the necessary power to drive this oscillatory system. In order to obtain a certain ROP in the presence of differing levels of the different efficiency, different input voltages can be examined. The system characteristics with three different harmonic input voltages will be analyzed by simulation results.

If the rock properties are known in advance, it is possible to develop a variable voltage variable frequency (VVVF) open loop control scheme for the tubular RTPMSM with a short stroke as previously reported in [8]. The simulation results show that VVVF control can achieve the expected performance. If the three-phase tubular RTPMSM with long stroke is utilized in the DTH hammer drilling system, self-sensing (sensorless) control is necessary because of the harsh conditions of high temperature and pressure.

5. Simulation Results

Simulation results are shown in Fig. 4-Fig. 7.

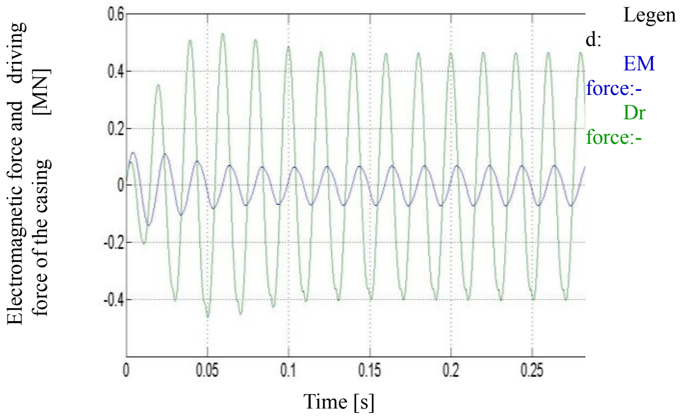

Fig. 4. Force amplification with a cosine wave input voltage

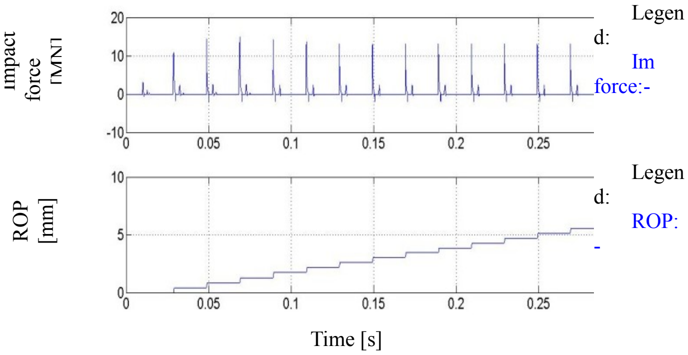

Fig. 5. Impact force and ROP with cosine wave input voltage

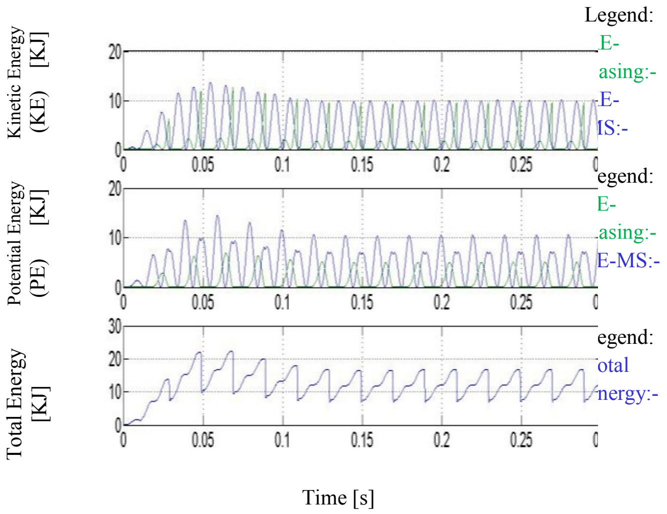

Fig. 6. Energy analysis

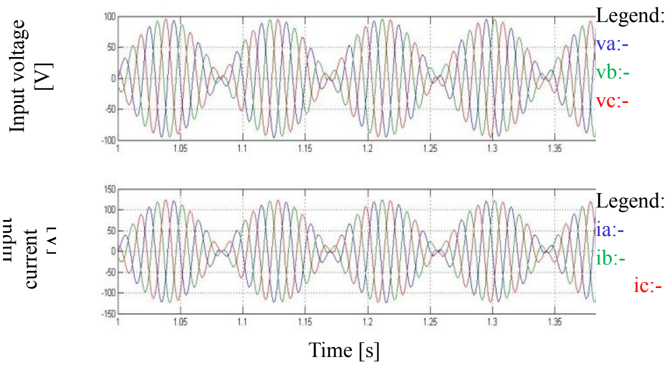

Fig. 7. Input voltage and input current

Fig. 4 shows the force amplification with a cosine wave input voltage. The electromagnetic force is amplified five times by the system. It means that only a small force is needed in order to drive the casing when employing such a tubular RTPMSM. Fig. 5 shows that a 14 mega Newton impact force is achieved at the instant of impact while the electromagnetic force is at 0.08 mega Newton. The system gets a 0.42mm penetration at each impact. There are second impacts after each main impact. The reason for these phenomena is because the rock model has the effect of a spring. A fraction of the energy is reflected to the casing by the rock at the instant of impact. This reflected energy introduces a second impact to the rock. However, the second impact does not contribute ROP because of its low energy, which is not enough to crush the rock.

The energy transfer from the RTPMSM to the rock is shown in Fig.6. The kinetic energy and potential energy of subsystems periodically change their values from zero to their maximum value, respectively. A part of total energy stored in the RTPMSM is delivered to crush the rock at the instant of impact. The reason for this is that only the kinetic energy of the casing is delivered to the rock. The kinetic energy and potential energy are still there as long as the velocity and relative displacement of the moving secondary are not zero. Fig.7 shows that the amplitude of the input voltage and current is always changing from cycle to cycle at steady state. The phase sequence is also changing at zero crossing points of the electromagnetic force. The reason for this is that the force command is a sinusoidal waveform. The amplitude and frequency of the current vector are dependent on the force command.

6. Optimization of Input Voltage

Different input voltage waveforms can achieve the same ROP on rock possessing the same properties, but with different losses. Therefore, the optimization of the input voltage waveforms is included in this work. Based on Fourier series theory, a perfectly periodic input voltage can be decomposed into simple oscillating functions which are harmonically related, but different frequencies. Only the fundamental harmonic contributes to the oscillation of the RTPMSM and all the other components will produce the losses and have little or no contribution, or less contribution, to the oscillation. Therefore, a pure sine (cosine) waveform will be the best option for maximizing the oscillation and minimizing the losses. Three different input voltages are used to drive the RTPMSM:

$$v_{q1}^{*}(t) = A\cos(\omega_n t) \tag{10}$$

$$v_{q2}^{*}(t) = A\frac{1-\cos(2\omega_n t)}{2}\frac{4}{\pi} \tag{11}$$

$$v_{q3}^{*}(t) = A\left[\frac{1-\cos(2\omega_n t)}{2}\right]^2\frac{16}{3\pi} \tag{12}$$

Fig. **8** shows that three different input voltages with the same amount of energy in each cycle are causing the tubular RTPMSM to oscillate. The system driven by different waveforms of input voltage shown in

Fig. **8** has different ROPs, although each waveform draws the same amount of energy from the electric source. The reference signal v_{q2}^{*} producing the least losses and the biggest ROP can be a good option of reference for the RTPMSM.

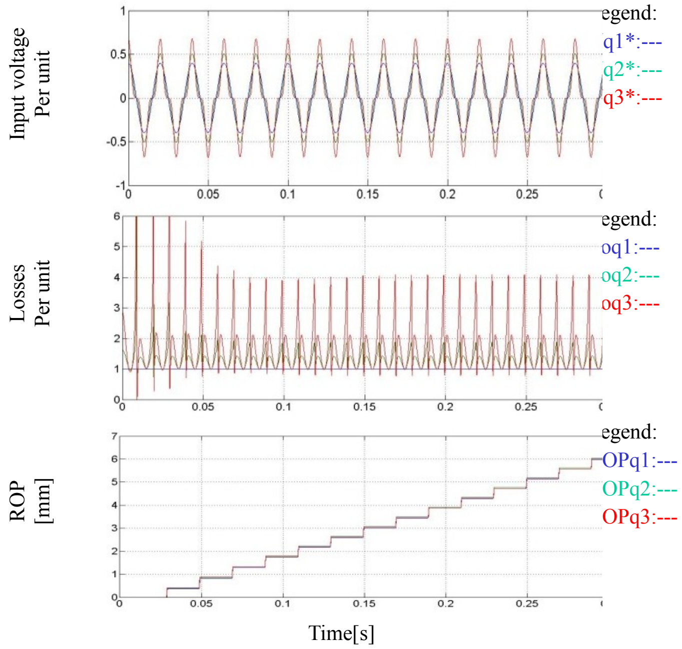

Fig. 8. System performance with three different input

7. Conclusion

The percussive drilling application of an RTPMSM and its mathematic model are presented in this work. The RTPMSM draws and stores energy during most of each oscillatory cycle and delivers it to the rock at the instant of impact. The huge impact force produced by the RTPMSM is delivered to crush the rock. Simulation results show that RTPMSM is suitable for percussive drilling application, especially for the offshore oil & gas industry. The optimization of input voltage waveforms is also done in this work. The simulation result shows that the second harmonic input produces higher ROP than the others.

Acknowledgement

The authors would like to thank Resonator AS for supporting this work. S. Zhang thanks Wisconsin Electric Machine and Power Electronics Consortium (WEMPEC) at the University of Wisconsin-Madison for inviting him to do the exchange study.

References

[1] G.R. Samuel, "Percussion Drilling.Is It a Lost Technique? A Review ," in SPE 35240, the Permian Basin Oil & Gas Recovery Conference, Mildland,TX, USA, 1996.

[2] Gang Han, Mike Bruno, and Khang Lao, "Percussion Drilling in Oil Industry: Review and Rock Failure Modelling," in the AADE 2005 National Technical Conference and Exhibition, Houston, 2005.

[3] (2011, May) wassara. [Online]. http://www.wassara.com/

[4] Göran Tuomas, "Water Powered Percussive Rock Drilling---Process Analysis, Modelling and Numerical Simulation," Luleå University of Technology, Luleå, Sweden, PhD thesis 1402-1544, 2004.

[5] R.B. Ummaneni, R. Nilssen, and J.E. Brennvall, "Demonstration model of a linear permanent magnet actuator with gas springs," in Electrical Machines, 2008. ICEM 2008. 18th International Conference on, Wuhan, China, 2008, pp. 1-4.

[6] Shujun Zhang, Lars Norum, and Robert Nilssen, "Oscillatory motion application of tubular linear permanent magnet machine," in Industrial Electronics, IECON'09. 35th Annual Conference of IEEE , 2009, pp. 1223-1227.

[7] M. S. Sazidy, D. G. Rideout, S. D. Butt, and F. Arvani, "Modeling Percussive Drilling Performance Using Simulated Visco-Elasto-Plastic Rock Medium," in the 44th US Rock Mechanics Symposium and 5th U.S.-Canada Rock Mechanics Symposium, Salt Lake City, 2010, pp. 10-434.

[8] Shujun Zhang, Lars Norum, and Robert Nilssen, "Variable voltage variable frequency control of tubular linear permanent magnet synchronous machine for drilling applications ," in Electrical Machines (ICEM), 2010 XIX International Conference on , Rome, 2010, pp. 1-5.

Shujun Zhang was born in Hebei, China. He received the M.Sc. degree from Tianjin University of Technology in 2006 and Ph.D. degree from Norwegian University of Science and Technology in 2012, respectively. He is currently a senior development engineer at Siemens As, Norway. His research interests include power electronics, electric drives and renewable energy.

Lars E Norum received his MSc and PhD degrees in Electrical Engineering from the Norwegian Institute of Technology (NTH), Trondheim in 1975 and 1985 respectively. From 1975 to 1980 he was a member of the research staff at the Norwegian Electric Power Research Institute. He then joined the Norwegian University of Science and Technology (NTNU), where he is currently a Professor in Industrial/Power Electronics at the Faculty of Information Technology Mathematics and Electrical Engineering. He served as Head of the Department of Electrical Power Engineering at NTNU (1996-2000). Presently his research activities are within the field of digital and analogue signal processing, mathematical modelling and control of electrical energy conversion in renewable energy systems. Dr. Norum has been a member of IEEE since 1989, and ISES since 2003. He has served as President for the Board of Science and Technology at the Norwegian Society of Chartered Engineers (1997-2001).

Robert Nilssen received his B.S., M.S., and PhD degrees from Norwegian University of Science and Technology Nilssen's PHD thesis was on development of field calculation programs based on the use of commercial codes for FEM and graphical Pre and post processing. After his PhD study he participated in a series of academic and industry projects, in which the use of 2D and 3D analysis programs was requested. Both FEM and BEM algorithms have been used. A wide range application are have been hanfled, but the most important application is electrical machines. When Robert Nilssen became professor in 1996 he focused more on Permanent Magnet electrical machines in which field calculations and optimization has been the focus point. He was also in 1996 the cofounder of the company SmartMotor in Norway, in which 40 engineers now are working on various electrical machines projects.

Robert D. Lorenz (S'83–M'84–SM'91–F'98) received the B.S., M.S., and Ph.D. degrees from the University of Wisconsin, Madison, and the M.B.A. degree from the University of Rochester, NY. Since 1984, he has been a member of the faculty of the University of Wisconsin-Madison, where he is the Mead Witter Foundation Consolidated Papers Professor of Controls Engineering in the Department of Mechanical Engineering. He is Co-Director of the Wisconsin Electric Machines and Power Electronics Consortium (WEMPEC). It is the largest industrial research consortium on motor drives and power electronics in the world. Prior to joining the university, he worked 12 years in industry, in Rochester, New York, principally on high performance drives and synchronized motion control. He has authored over 260 published technical papers and is the holder of 24 patents with seven more pending. He has won 27 IEEE prize paper awards on power electronics, drives, self-sensing, current regulators, etc.

Dr. Lorenz is a Fellow of the IEEE, was IEEE Division II Director for 2005/2006, was the IEEE Industry Applications Society (IAS) President for 2001, a Distinguished Lecturer of the IEEE IAS for 2000/2001. He received the 2003 IEEE IAS Outstanding Achievement award, 2006 EPE PEMC Outstanding Achievement award, and 2011 IEEE IAS Distinguished Service Award.