Calculation of the Losses of Series-Hybrid Powertrains

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Abstract: Regarding mobile machinery, particularly agricultural tractors, there is an ongoing competition for the most suitable technology to achieve optimum functionality with maximum efficiency. In this competition, the efficiency of electric series-hybrid powertrains (ESHPs) is often depicted as worse than the efficiency of mechanical-hydraulic power-split powertrains (MHPSPs). On closer inspection of these statements, however, systematic errors, such as unequal balance limits, neglected size effects and nonlinearities, non-observance of recent technical developments and standards, or erroneous application of research results regarding MHPSPs on ESHPs are often evident. For verification (and under avoidance of the systematic errors mentioned above), the losses of an ESHP of 150 kW power are for example calculated and compared with the losses of a typical MHPSP of the same power. The comparison of the losses shows that the ESHP clearly exceeds the efficiency of the comparative MHPSP in the main working range and that there is still potential for improvement.

Key words: Electric tractor, series-hybrid powertrain, electric propulsion, calculation of losses, mechanical-hydraulic power split, drive inverter.

1. Introduction

Since the presentation of the ELTRAC[®]-tractor [1], the first tractor with an electric series-hybrid powertrain (ESHP) using modern inverter technology in 1998, there is an ongoing competition with the previously introduced mechanical-hydraulic power-split powertrains (MHPSPs) in terms of their efficiencies, benefits and future development potentials. In recent literature on agricultural tractors (and on other mobile machines as well), however, the efficiency of the upcoming ESHPs is often reported to be worse than the efficiency of the available MHPSPs [2-4], whose power-split principle can also be used for mechanical-electric power-split powertrains (MEPSPs) [5]. But, according to Morselli [6] the efficiency of electric machines is so high that the efficiency of an MEPSP is worse than that of an ESHP even for a 50 kW-tractor (which is proved in Ref. [7]), while the

efficiency of an MHPSP for the same tractor is reported to be still 5% higher than that of an ESHP. All these statements are in contradiction to the overwhelming knowledge on electric and hydraulic propulsion. This contradiction is to be investigated here.

2. Applied Methods

With regard to the relevant tractor size in Europe (and North America as well), the investigation is performed for an example ESHP with 150 kW power. For this purpose, a general model of a typical MHPSP is defined, and the limits of the investigation are fixed. Then, the losses of the comparative powertrain are calculated and verified. In two further steps the analysis of the single components of the ESHP as well as the approximate calculations of the losses caused by them is carried out. From the subsequent comparison, analysis and discussion, the core statements of this paper are derived.

3. Modeling

Although classic vehicle manufacturers prefer parallel hybrid, electric power-split or series-hybrid powertrains with electric single-wheel drives, here the

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ESHP is based on powertrains, as they are used in vehicles with an external energy supply (for example trolleybuses, trams, also those with inductive energy supplies, and Siemens-eHighway trucks [8] or as range-extenders in battery electric vehicles). However, the advantage of certain systems depends very much on their particular application. According to Schmetz [9], an ESHP is the most suitable for larger agricultural tractors, if advantageous also in combination with drive axles. On base of further calculations and in contradiction to Geimer and Renius [4], it can also be shown that electric single-wheel drives are not advantageous for standard tractors. Main advantages of ESHPs for larger tractors are:

- (1) Very good integration into existing tractor concepts;
- (2) Very good suitability for electric machines of high efficiency;
- (3) Very good utilization of electric machines and power electronics;
- (4) Very good controllability of the powertrain;
- (5) Cost-effective solution with a very good ratio of technical to economic value.

The powertrain of the ELTRAC[®]-tractor according to the left part of Fig. 1 is the best way to calculate the losses of an ESHP and to compare it with the losses of an MHPSP. This powertrain has a typical tractor engine and a typical final drive unit, consisting of a bevel and a differential gear, two planetary gears for

the rear wheels and a power take-off to the front axle, which is not shown. In case of rectilinear driving, the differential gear can be assumed to be at standstill or locked and therefore be neglected. Both the tractor engine and the final drive are interchangeable with conventional tractors. If the savings according to Schmetz and Kett [1] and Schmetz [9], which can be achieved beyond the efficiency level of an ESHP, are not considered, only the unit in the balance limit (consisting of the electric machines, the rectifier and the inverter) and the two-stage gearbox outside still require adequate counterparts. Thus, the model of the MHPSP (right part of Fig. 1) requires the same assemblies as the medium-sized Agco-Fendt Vario-tractors whose data are readily available. With regard to the presence of comparable two-stage gearboxes in both powertrains, these can also be clamped out. Finally, this provides good comparability and allows the reduction of the comparison to the two units in the balance limits.

4. Rough Calculation of the Losses in the Comparative Powertrain

The efficiency of the MHPSP is:

$$\eta_{\text{MHPSP}} = [S \times \eta_M + (1 - S) \times \eta_H] \quad (1)$$

The split factor S ($0 \leq S \leq 1$) gives the proportion of the mechanically transmitted power and the term $(1 - S)$ the proportion of the hydraulically transmitted power. The efficiencies η_M and η_H take the losses in the mechanical (M) and hydraulic (H) branches into

Fig. 1 Electric series-hybrid and mechanical-hydraulic power-split powertrains.

account. An efficiency of 97% for the split gear (planetary gear with a driven arm, three internal meshing contacts and a drive-through shaft) and an overhead of 1% for pressure lubrication, oil splashing and friction (e.g., by bearings and seals) lead to $\eta_M = \sim 0.97 \times 0.99 = \sim 0.96$. The efficiency η_H is made up of the mechanical losses η_{H-M} in the hydraulic branch, the volumetric and hydro-mechanical losses of the pump and the motor of the hydrostat, as well as the effort for the auxiliary units to

$$\eta_H = \eta_{H-M} \times \eta_{\text{Volumetric (Vol)-Pump (P)}} \times \eta_{\text{HydroMechanical (HM)-P}} \times \eta_{\text{Vol-Motor (M)}} \times \eta_{H-M} \times \eta_A \quad (2)$$

An efficiency of 98% for the split gear (planetary gear with one driven arm and three external meshing contacts) and 99% for each out of the two spur gear sets (hydrostat reducer and power merging gear set) and a 1% cut for pressure lubrication, oil splashing and friction lead to $\eta_{H-M} = \sim 0.98 \times 0.99 \times 0.99 \times 0.99 = \sim 0.95$. The efficiency of the auxiliary units of the hydraulic branch, such as the losses of the charge pump and the overload protection as well as the filter and flushing circuits of the hydrostat, is considered by the efficiency $\eta_A = 98\%$. The losses of the fans of the radiator circuit are not taken into account. However, the efficiency of the hydrostat has yet to be determined. According to Rahmfeld and Skirde [3], the best efficiency of a hydrostat is 96% at its peak. A closer look, however, reveals that this efficiency was not determined due to the ISO 4409-standard, since the measurements were performed with a single (two-shaft) electric motor (thus with a fixed displacement ratio). In addition, impacts by auxiliaries were neglected and the oil ISO-VG 11 was used instead of ISO-VG 46, which is recommended for the hydrostat of the comparative powertrain. Because of these deficiencies, real efficiencies of hydrostats are lower. According to other sources, even high efficient hydrostats have only efficiencies of 90% at their peaks [2, 10-13]. Therefore a (still high) hydrostat efficiency $\eta_{\text{Hydrostat}} = \eta_{\text{Vol-P}} \times \eta_{H-M} \times \eta_{\text{Vol-M}} \times \eta_{H-M} = \sim 0.9$ is applied here. Then the efficiencies are $\eta_H = 0.95 \times 0.9 \times 0.98 = 0.84$ for the

hydraulic branch and $\eta_{\text{MHPSP}} = [S \times 0.96 + (1 - S) \times 0.84]$ for the MHPSP in the balance limit. Depending on the split factor S , the resulting efficiencies of the MHPSP are shown in Table 1. The main working range of a tractor is usually at $S \approx 0.25$ with high engine utilization and the maximum transport speed is usually at $S \approx 1$ with significantly reduced engine utilization. The maximum transmissible power close to $S \approx 0$ is limited by the size of the hydrostat. It is not taken into account that the efficiency is also adversely affected by the unavoidable idle losses of the hydrostat even at $S = 1$. In addition, operating ranges with positive ($S < 0$) and negative ($S > 1$) circulating power are not considered. The above calculations are confirmed by performance tests carried out by the German Agricultural Society's test center in Groß-Umstadt. There, a maximum tractive power of 137.5 kW corresponding to an efficiency of 0.78 was measured for an Agco-Fendt Vario-tractor 724 with a powertrain according to the right part of Fig. 1 and a maximum engine output of 176.4 kW at 1,700 rpm [14]. If this efficiency is corrected by the losses of the two-stage gearbox and the final drive, which is about 6% to 7% according to Geimer and Renius [4], a good match is obtained with the calculated efficiency in the main working range, where the maximum drag power should appear.

5. Components of the ESHP

5.1 Electric Machines

Due to content restrictions, the electric machines cannot be described in detail here. But it is important to know that the former European Committee of Manufacturers of Electrical Machines and Power

Table 1 Calculated efficiencies of the mechanical-hydraulic power-split powertrain (MHPSP).

Split factor S	Efficiency η_{MHPSP}
0	0.84
0.25	0.87
0.5	0.90
0.75	0.93
1	0.96

Electronics (CEMEP) efficiency classes (EFF) were restricted to electric machines up to 90 kW. This may be one of many reasons why larger electric machines have received little attention in powertrains for off-road applications for long periods of time, despite their ability to deliver constant power with high efficiency across large operating ranges, if operated in combination with a suitable inverter (thus in systems, which are called IES1 or IES2 due to the European Standard EN 50598-2). Since 2011, in the European Union the new IE efficiency classes according to the International Electrotechnical Commission (IEC) standard IEC 60034-30:2009 apply for electric machines up to a power of 375 kW. Due to this standard the new IE3-types (more efficient than the former EFF1-electric machines) were introduced, followed up by an amendment (IEC 60034-30-1:2014) defining a new IE4-standard, mentioning already a future IE5-standard, expanding the application range for standard electric motors to powers from 0.12 kW to 1,000 kW, as well as making information about part load-efficiencies mandatory (Fig. 2). It should be noted, that the full-load efficiencies slightly increase with increasing speed (see efficiencies at 60 Hz frequency instead of 50 Hz) or by stepping down to 75% load.

With regard to the standard, here the (minimum) required efficiency of 95.6% can be applied to the electric motor. In contrast, asynchronous generators are rarely used in ESHPs. Synchronous generators are more common, which have a slightly higher efficiency of about 96% at a power of 150 kW.

5.2 Power Processing Unit (PPU)

The most common configuration of the PPU of an ESHP (without energy recovery when braking) is shown in the upper half of Fig. 3. The PPU contains a rectifier, a direct current-link (DC-link) with smoothing capacitor(s) and a brake resistor, and an inverter with six insulated gate bipolar-transistors (IGBTs) with free-wheeling diodes. The two IGBTs with free-wheeling diodes required for each phase are available as a ready-to-use module (or all six IGBTs as a six-pack) whose gates only have to be connected to a low-power driver unit. This driver unit generates width-modulated pulses depending on the operating state. Another IGBT is required for the actuation of the brake resistor. In line with a controlled three-phase alternating current-synchronous generator (AC-synchronous generator) an uncontrolled rectifier can be used. Most commonly this is a bridge 6-rectifier (B6-rectifier) consisting of

Fig. 2 IE classification for 50 Hz 4-pole electric motors according to IEC 60034-30-1:2014.

six power-diodes arranged as bridges from each single phase to the two lines of the DC-link. A typical power-diode characteristic is shown in the lower left part of Fig. 3. When a single-phase AC of 100 A with a voltage of 500 V is rectified, the losses while conducting during the positive half-wave are about 100 W and while blocking during the negative half-wave about 7 W (for a power-diode like International Rectifier-1N2067 (IR-1N2067)). It should be noted, that a B6-rectifier cannot pass the full available power. This is expressed by the so-called power factor λ_R which is 0.955 for a B6-rectifier. This means that a generator must be designed for an apparent power of approximately 157.1 kVA for the supply of 150 kW power at continuous duty to a DC-link via a B6-rectifier despite the much lower losses of its diodes. In special applications, ACs with

more than three phases can be generated and rectifiers with more than six pulses can be used. Then, the current from the DC-link is converted again by an inverter to a three-phase AC, but now with its amplitude and frequency adjustable.

The simplified switching pattern of a single IGBT of such an inverter is illustrated in the lower right part of Fig. 3. When switching an IGBT, the voltage and the current do not change immediately. In reality, short delays occur, before the voltage falls from the blocking voltage U_{block} to the on-state voltage U_{cond} of the IGBT at the end of the switch-on operation, as well as rises vice-versa from the on-state voltage U_{cond} to the blocking voltage U_{block} at the end of the switch-off operation [15-18]. A free-wheeling diode is required in order to avoid voltage peaks in the reverse direction, which occur during the switch-off of inductive

Fig. 3 Power processing unit (PPU).

loads like here. As a result, a significantly higher loss occurs during the switching of an IGBT in contrast to a passive power-diode. Typical switching (or modulation) frequencies of the IGBTs in inverters for AC-asynchronous motors of a size like here are 1-4 kHz. With regard to these losses, the losses during conduction and blocking are only slightly higher than in the case of a power-diode. In addition, driving the metal oxide semiconductor-gate (MOS-gate) of an IGBT also requires electrical power that has to be taken into account. But, in relation to the base or gate power, which conventional semiconductors require, this power is low. For rough calculations of the losses in ESHPs, the simplified switching pattern of an IGBT shown in Fig. 3 is sufficient. For a closer inspection the Infineon-dimensioning tool IPOSIM[®] and its technical documentations [19, 20] can be used. Typical values for the following calculations are taken from datasheets like for those of Infineon IGBT-modules FF200R12KT4 or IGBT-six-packs FS200R12KT4R.

6. Rough Calculation of the Losses in the ESHP

Since the input power of the ESHP equals the output power of the attached internal combustion engine $P_{\text{Internal combustion engine (ICE)}}$, the nominal output power of the generator $P_{\text{Generator (G)}}$ can be calculated by:

$$P_G = P_{\text{ICE}} \times \eta_G = 3 \times U_G \times I_G / \sqrt{3} \quad (3)$$

Then, for an input power of $P_{\text{ICE}} = 150$ kW, an output voltage of the generator of $U_G = 500$ V 3~(Δ), and an efficiency of $\eta_G = 0.958$ an output current of the generator of $I_G = 165.9$ A is obtained. Assuming (for the most critical case) the equivalents of one power-diode per phase as permanently conducting and of the remaining power-diode as permanently blocking, the losses of the B6-rectifier are:

$$P_{\text{Rectifier (R)-loss}} = 3 \times U_{\text{D-loss}} \times (I_G / \sqrt{3}) + 3 \times U_G \times I_{\text{D-leakage}} \quad (4)$$

Consequently, the losses of the B6-rectifier are $P_{\text{R-loss}} = 308.4$ W.

Taking these losses into account the output power of the B6-rectifier is $P_R = 143.4$ kW and its efficiency $\eta_R = 0.998$. Furthermore, in the DC-link the voltage can be determined by Eq. (5):

$$U_{\text{DC(-link)}} = U_G \times \sqrt{2} \quad (5)$$

Thus, the voltage in the DC-link is $U_{\text{DC}} = 500$ V $\times \sqrt{2} = 707$ V. The current in the DC-link can be calculated by:

$$I_{\text{DC}} = P_R / U_{\text{DC}} \quad (6)$$

Therefore this current is $I_{\text{DC}} = 202.8$ A. The losses caused by leakages of the DC-link capacitor(s) and the IGBT for the actuation of the brake resistor can be neglected in the case of a rough calculation since they are usually smaller than 10 W. Furthermore, this IGBT is only actuated in case of sudden braking processes, while the kinetic energy, which is set free in the comparative MHPSP, is deleted by mechanical brakes. In contrast, the six IGBTs of the inverter, which are also arranged in a B6-configuration like the diodes of the rectifier, are permanently forced on and off by controlled pulses within single periods T , which corresponds to the inverse of the pulse width modulation frequency f . Therefore, this configuration is called B6C_{controlled} (B6C). The periods T consist of the following four components like already shown in the lower right part of Fig. 3:

$$T = 1/f = t_{\text{turn-on}} + t_{\text{conducting (cond)}} + t_{\text{turn-off}} + t_{\text{blocking (block)}} \quad (7)$$

Again, assuming (for the most critical case) one IGBT per phase as permanently on and the remaining IGBT as permanently off, the maximum conduction time per IGBT is $t_{\text{cond}} < 50\%$ of a full period T ($t_{\text{cond}} \leq (T/2) - t_{\text{turn-on}} - t_{\text{turn-off}}$) and the minimum blocking time per IGBT is $t_{\text{block}} \geq 50\%$ of a full period ($t_{\text{block}} \geq T/2$). Then, with a typical power demand of a single driver unit of $P_{\text{Gate emitter (GE)}} = 60$ W at $I_{\text{cond}} = 120$ A during actuation of an IGBT-gate, this results in inverter losses of $P_{\text{Inverter (I)-loss}}$ as follows:

$$P_{\text{I-loss}} = f \times [6 \times 0.5 \times U_1 \times (I_{\text{DC}} / \sqrt{3}) \times (t_{\text{turn-on}} + t_{\text{turn-off}}) + 6 \times U_{\text{cond}} \times (I_{\text{DC}} / \sqrt{3}) \times t_{\text{cond}} + 6 \times U_1 \times I_{\text{leakage}} \times t_{\text{block}} + 6 \times P_{\text{GE}} \times (T/2)] \quad (8)$$

In addition, a resulting boundary condition for the assumed case can be derived:

$$(T/2) = t_{\text{turn-on}} + t_{\text{cond}} + t_{\text{turn-off}} = t_{\text{block}} = 1/(2 \times f) \quad (9)$$

Using this boundary condition, the most critical pulse width modulation frequency of $f = 4$ kHz, and $U_1 = U_{\text{DC}}/\sqrt{2}$ the maximum inverter losses are $P_{1-\text{loss}} = 1,190$ W. Thus, the output power of the inverter is $P_1 = 142.2$ kW and its efficiency $\eta_1 = 0.992$. Although the power factor of an inverter can usually be controlled close to $\lambda_1 = 1$, it should be noted, that an inverter in an application like here needs an overload capacity of a factor two, which is narrowly fulfilled for the semiconductor-types mentioned above. Taking that into account, the nominal power of the three-phase asynchronous motor, which is operated with the output voltage of the inverter $U_1 = 500$ V 3~ and which has an efficiency of $\eta_{\text{Elektric motor (E)}} = 0.956$ as given earlier, can then be calculated by:

$$P_E = P_1 \times \eta_E \quad (10)$$

This leads to an output power of $P_E = 135.9$ kW. Furthermore, any additional losses caused by auxiliaries like pumps for a liquid cooling of the electric machines and the PPU are considered by the efficiency $\eta_A = 0.99$. Then the overall efficiency of the ESHP is:

$$\eta_{\text{Serial hybrid (S)}} = \eta_G \times \eta_R \times \eta_1 \times \eta_E \times \eta_A \quad (11)$$

Thus, the efficiency of the ESHP can be finally calculated to $\eta_S = 0.958 \times 0.998 \times 0.992 \times 0.956 \times 0.99 = 0.9$, which clearly exceeds the efficiency of the comparative MHPSP in the main working range.

7. Comparison, Analysis and Discussion of the Results

The rough calculation of the efficiencies of the examined ESHP with the comparative MHPSP results in an efficiency advantage of 3% in favour of the EHSP. A closer look at the specified boundary conditions, the neglected losses such as those caused by circulating powers and at idling, and the described

characteristics of the two comparative powertrains also shows that the advantage of the ESHP is even higher for part-load applications in a wide working range. This is due to the fact, that large electric machines are more efficient down to partial loads of less than 50% as well as over a wide speed range from less than half up to more than twice of their rated speed, while the best efficiencies of hydrostatic units fall off considerably even at smaller deviations from their peaks.

Another finding is that in a lot of recent comparisons of the properties of ESHPs and MHPSPs the size influence of the drives has not sufficiently been considered. Precisely because the relative losses decrease with the size, calculations of efficiencies should always be made with the absolute values. The same applies to the influence of the PPU on the overall efficiency of an ESHP, although its contribution to the overall loss of an ESHP is much smaller than claimed in recent literature like Ref. [4]. The reason for that seems simply to be, that in this literature the remarkable improvement, which was achieved in the last two decades, has not been taken into account so far.

However, the likely increase in the mass of a tractor by some hundred kilograms, which is not necessarily detrimental, is not picked out as a central theme in this paper. Furthermore, the main drawbacks for a widespread application of ESHPs so far, thus safety and cost issues, are not investigated here in more detail. But, while the safety issues can be managed like in common electric vehicles, for the probable increase in mass and cost, the trend, which was already mentioned in 1998 in Ref. [1] and which has continued since then and will continue into the future, is slowly changing the cost relations. According to it, the sizes of the PPU and the dimensions of all components and their prices will continue to be forced down by the production of larger quantities and the application of new research results.

8. Conclusions

Finally, the following statements can be derived:

(1) The losses in EHSPs are caused by the electrical machines rather than the PPU's;

(2) An ESHP of 150 kW power clearly exceeds the efficiency of the comparative MHPSP in the main working range;

(3) By the use of more efficient (e.g., IE4) electric machines and further optimized inverters (e.g., by the use of silicon-carbide made semiconductors) further improvements in efficiency of ESHPs are still possible.

References

- [1] Schmetz, R., and Kett, J. 1998. "New Product Technologies in Tractor Design, Especially Electromechanical Tractor Powertrains." In *Proceedings of the 56th International Conference Agricultural Engineering (VDI-Report No. 1449)*, Munich, 1-6. (in German)
- [2] Renius, K. T., and Resch, R. 2005. "Continuously Variable Tractor Transmissions." *ASAE Distinguished Lecture Series, Tractor Design No. 29*: 14-22.
- [3] Rahmfeld, R., and Skirde, E. 2010. "Efficiency Measurement and Modelling." In *Proceedings of the 7th International Fluid Power Conference Vol III*, Aachen, 53-66.
- [4] Geimer, M., and Renius, K. T. 2012. "Engines and Transmissions for Tractors." *Yearbook Agricultural Engineering*, Vol. 24, edited by Frerichs, L. Braunschweig: Institute of Mobile Machines and Commercial Vehicles, 69-77. (in German)
- [5] Schmetz, R. 1999. "Agricultural Machine with Mechanic-Electric Power-Split Powertrain." *German Patent No. DE4425387*, Munich. (in German)
- [6] Morselli, R. 2014. "Electrification in Ag." In *Proceedings of the 5th International Colloquium Electrical Drives in Agricultural Machines*, 2nd Session, Dresden, 1-21.
- [7] Schmetz, R. 2015. "Rough Calculation of Losses in Series-Hybrid Powertrains." In *Proceedings of the 5th Conference Hybrid and Energy Efficient Drives for Mobile Machines*, Karlsruhe, 141-60. (in German)
- [8] Siemens, A. G. 2012. "Into the Future—With eHighway. Innovative Solutions for Road Freight Traffic." *Siemens Publication No. A19100-V350-B135-X-7600*, Munich, 6-7.
- [9] Schmetz, R. 2011. "Electric Tractor Powertrains." In *Proceedings of the 14th Heavy Drive Train Conference*, Aachen, 77-101. (in German)
- [10] Ivantysin, J. 1993. *Hydrostatic Pumps and Motors: Design and Dimensioning*. Würzburg: Vogel-Publishing House, 461-91. (in German)
- [11] Renius, K. T., and Vahlensieck, B. 1996. "Efficiencies of Continuously Variable Tractor Transmissions." *Landtechnik* 51 (May): 248-9. (in German)
- [12] Kohmäscher, T. 2008. *Modeling, Analysis and Design of Hydrostatic Powertrain Concepts*. Aachen: Shaker Publishing House. (in German)
- [13] Murrenhoff, H. 2012. *Fundamentals of Fluid Technology*, 7th ed. Aachen: Shaker Publishing House, 348-68. (in German)
- [14] Wilmer, H. 2013. "No or an Expensive Fun." In *Profi: The Farm Machinery Magazine*, Münster: Landwirtschaftsverlag, 12-8. (in German)
- [15] Mohan, N., Undeland, T., and Robbins, W. 2003. *Power Electronics*. 3rd ed. Minneapolis: Wiley.
- [16] Mohan, N. 2012. *Power Electronics: A First Course*. Minneapolis: Wiley.
- [17] De Doncker, R. W. 2013. *Lecture Notes Power Electronics: Fundamentals, Topologies. Analysis*, 4th ed. Aachen: Institute for Power Electronics and Electrical Drives (ISEA), 17-8.
- [18] Volke, A., and Hornkamp, M. 2017. *IGBT Modules: Technologies, Driver and Application*, 3rd ed. Munich: Infineon Technologies AG.
- [19] Infineon Technologies AG. 2006. *Technical Documentation: Dimensioning Program IPOSIM® for Loss and Thermal Calculation of Infineon IGBT Modules*. Infineon Technologies AG Warburg.
- [20] Infineon Technologies AG. 2015. *IPOSIM®: The Infineon Power Simulation Program for Loss and Thermal Calculation of Infineon Power Modules and Disk Devices: Step by Step Guide*. Infineon Technologies AG. Accessed August 24, 2017. <http://www.infineon.com/Infineon-IPOSIM>.