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Efficiency-optimal power partitioning for improved partial load efficiency of electric drives

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ABSTRACT

In this paper, the global power conversion efficiency is improved for a fault-tolerant drive architecture. The fault-tolerant architecture is obtained by combination of a 3-phase open-end winding machine and a 3H-bridge inverter. This combination offers more degrees of freedom for the control strategy than a classical 3-leg inverter. This paper demonstrates that the additional degree of freedom of this power system can be exploited for efficiency optimization purposes in normal operation mode. In the present work, the retained optimization criteria is the minimization of the drive losses which is a critical issue. In addition, to fulfill the torque demand, this leads to a constrained optimization problem which can be analytically solved using the Lagrange multipliers method. Besides, as each motor phase can be driven independently, the resolutions for three strategies, i.e. for three, two or one-phase simultaneous conduction of the inverter, provide three different optimal current waveforms. This is the key point of the proposed efficiency-optimal power partitioning for improved partial load efficiency of electric drives. Finally, on a test bench, the real-time tracking of the mentioned current waveforms is successfully tested and power measurements confirm the possibility of using the three different control strategies to realize an efficiency optimum phase-shedding strategy.

1. Introduction

Efficiency improvement in energy conversion process is becoming a primary development goal in many applications, in connection with rising energy prices and resources conservation. This is, in particular, the case in various areas such as embedded applications [1], communication networks [2], data centers [3], electric grid generation [4–6], or automotive applications [7]. The following part reviews best practices for enhancing the power converter efficiency for electric drives. Some efficient techniques can be found in the power converters for photovoltaic systems mainly. Indeed, photovoltaic inverters achieved in 2015 a rated power efficiency higher than 99%, driven by the market demand. This significantly exceeds the reference value of 95% of year 2000 [8–11]. Similarly, pushed by high standards [12], converter stages of telecom power modules produce less than 1% of power losses at rated power [13]. Indeed, the clear requirement of this application, in terms of compactness and reliability, involves high power density while keeping a low operating temperature. Therefore, minimizing losses of power electronics systems gains increasingly in importance and power conversion efficiency tends to be a key criteria among the performance indices [14].

The rated power operating point is often used to define the performance of a system. However, in case of energy optimization considerations, the typical mission profile has to be considered, leading to assess the losses on different operating points [15]. This is particularly important for achieving a relevant energy efficiency optimization [16]. As an example, PV inverter certification requires not only full-load efficiency but also partial load values, namely at 10%, 20% and 50% of rated power [17].

Automotive applications also lead to a wide range of operating points [18]. In such applications, it is clearly demonstrated that the powertrain losses must be reduced for low power and low speed in order to increase the vehicle's autonomy [19]. For instance, to assess vehicles powertrain efficiency, a realistic average driving cycle such as ARTEMIS is used [20]. There are various ways of enhancing a power converter's efficiency: these include using new components [6], more complex topologies enabling soft-switching

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[21], or modular design [22,23], new designs with better integration [24], system considerations and innovative control procedures, e.g. Differential Power Processing [3]. All these considerations mainly lead to a global approach [14], e.g. of the optimization of the combination of the machine and the associated power electronics converters.

For single-cell converters, it should be noted that high efficiency at partial load leads to a significant increase of the performance of the system at full load [25]. Thus, partial load efficiency improvement is very difficult to achieve for classical converter topologies. Indeed, an efficiency of 90% at 10% partial load corresponds to a rated power efficiency of 99% under the assumption of constant losses over the entire output power range.

Experiencing the difficulty in obtaining a flat efficiency curve has led to the alternative solution of splitting a single converter into several smaller converters working in parallel [26]. The number of operating cells is defined to optimize the global power efficiency. Indeed, some of them can be disconnected and set off to improve efficiency when working at partial load. Choosing the number of operating converters with regard to the demanded power ensures that each subsystem works within a small power range around its best efficient operating point. This established control procedure is known as Phase Shedding or efficiency-optimal partitioning [27]. Toyota uses this strategy to manage a 114 kW boost converter implemented in the hydrogen-powered Mirai fuel cell electric vehicle (EV) [28]. The DC converter regulating the voltage delivered by the fuel cell is made of 4 parallel legs. The associated control determines in real-time the optimal number of cells to be used; this strategy leads to reduce the boost losses by ten per cent at 15 kW operating point [28]. This design also induces significant system improvements [25]: among the benefits, one could easily identify input and output current ripple reduction [29], a better continuity of service and also a fast transient response if using multiphase interleaved dc–dc converters, as in the case of the power management of microprocessors or double-data rate (DDR) memory [30]. With the goal of reducing power loss, the aforementioned system consideration has not yet been exploited in a motor drive.

Therefore the present paper applies a similar point of view to the approach in multiple parallel converters [8,27–30] to an electric motor drive designed to be fault-tolerant. This drive is the combination of a three-phase open-end-winding permanent magnet synchronous machine (PMSM) and a three-phase inverter made of three full H-bridges. This architecture has been patented for EV powertrain by the VALEO group, a world's leading automotive supplier [31–34]. Similarly to other three-phase structures, like neutral leg inverter or additional leg inverter [35], the VALEO patented option has the advantage of improved continuity of service due to its fault tolerant capability. In contrast, this solution has proved to be multifunctional without any additional device (i.e. electrical contactor), permitting EV traction [36,37], battery charging [38], power injection back to the grid during peak demand (vehicle to grid/V2G) and post-fault operating mode [39,40]. These are key features for specific applications like the EV emerging market. In traction mode, its key competitive advantage relies on its high degrees of freedom [41]. Unlike the combination of a classical three-leg inverter connected with a star- or delta-connected PMSM, each winding can be supplied independently. It makes the topology intrinsically fault-tolerant. Additionally in normal mode, thanks to this feature, the drive control can be operated using only one or two phases sequentially instead of three phases simultaneously. This option allows the increase the power dynamically in one or two phases and to cancel the power in the other phases. As the drive is running in normal mode, it opens up the possibility for choosing the best windings dynamically in order to minimize losses, while achieving the demanded torque. Thus, on an electric turn, each of the 3 phases converts power at the most appropriate moment.

In short, this article develops a method for normal operating optimized with respect to motor drive energy efficiency; the main idea consists in adjusting the number of phases in operation as a function of the required mechanical torque in order to maximize the drive power efficiency at low torque operating points. The paper is organized as follows. Section 2 addresses the optimized motor phase current shape in the general framework of non-sinusoidal PMSM back-electromotive force (back-emf). In Section 3, the drive current optimization method is applied in the three cases of one, two or three phases conducting simultaneously; in all these three cases, the phase current is derived analytically. Section 4 presents experimental validations of the innovative strategy. Finally, Section 5 draws conclusions and perspectives of the suggested approach.

2. Drive current optimization method

In the case of a sinusoidal magnetomotive force in a 3-phase synchronous machine, it is demonstrated that the optimal currents in the machine phases are sinusoidal and in phase with its electromotive forces [42]. These waveforms are, for a given electromagnetic torque, energetically optimal for the machine, as they minimize the RMS current values and hence the windings' Joule losses. In this case, cancellation of low frequency phase-voltage harmonics also enables the mitigation the machine ferromagnetic losses.

Now considering a more general drive current optimization, the design framework should integrate both losses in the machine and the power inverter for a 3-phase, 2-phase or 1-phase feeding sequence. In the following, any system loss will be taken into account.

A brief recall, underlying causes of losses in the machine–inverter association, allows better understanding of the guiding principle in developing the proposed strategy, based on an efficiency-optimal power partitioning (or fragmentation of power). The general problem of losses minimization that can be stated in terms of a constrained problem can be solved using the Lagrange multipliers method. The problem resolution using this method will be described at the end of the section.

2.1. Losses in the inverter and machine combination

Three loss-types with characteristic dependence on the output power P_O are occurring for a power electronic system [25]:

$$P_{losses} = k_0 + k_1.P_O + k_2.P_O^2 \tag{1}$$

The three parameters of this function are linked to various contributions:

1. k_0 expresses the power losses, which are independent of output power. This means:
    - Power feeding ancillary equipment, particularly the power needed by the IGBT driving cards as well as the cooling system, the sensors and the control card. In the present case, the strategy cannot act on the three last parameters;
    - Losses due to the power semiconductors parasitic capacitance that occur at each switching;
    - Machine core losses.
2. k_1 describes losses depending linearly on output power and is a consequence of:
    - Conduction losses in power switches, since diodes and IGBT are mainly characterized by a threshold voltage;
    - Switching losses in power switches.
3. k_2 defines losses with a quadratic dependency. This includes