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RESEARCH ARTICLE

# Offline Measurement of Stator Resistance and Inverter Voltage Drop Using Least Squares

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**ABSTRACT** Modern industrial and commercial electrical drives are typically designed to control motors of different types, operating under scalar, field-oriented or direct torque control. These drives execute various algorithm such as sensorless control, temperature monitoring, etc., which require the knowledge of motor drive parameters. In order to do this, the inverters allow data to be input manually or execute self-commissioning routines before running the motor. The parameters necessary for proper operation include motor phase resistance and inverter voltage drop, which are especially important in low-speed range. This paper presents an offline technique for estimation of mentioned parameters, which can be obtained with enough precision for the overwhelming majority of applications. The proposed algorithm consequently injects DC-current of several levels into the stator of a motor, measuring the corresponding voltages. Each pair of current and voltage is a point in the voltage current characteristic of motor drive, thus set of these points maybe approximated with a first order polynomial using least squares method. The parameters of polynomial are desired inverter voltage drop and phase resistance. The experimental section analyzes estimation errors and their dependence on the number of injected levels, their values and filtering capability of measuring algorithm. After that, the authors give suggestions on algorithm parameters selection, depending on the demanded precision. Finally, the authors demonstrate a mass-producing dishwasher motor drive, which adopted this technique.

**INDEX TERMS** Parameter estimation, electrical resistance measurement, voltage measurement, sensorless control.

## I. INTRODUCTION

Electrical motors play a significant role in modern society, consuming about half of the energy produced in the world [1]. As a result, even minor increases of motor drive efficiency have a significant positive impact on energy systems, decreasing power loss and fuels burn [2]. Considering the latest tendencies on decreasing carbon emissions, these facts are the key reasons for toughening of standards on device efficiency, which force manufactures to increase efficiency of their devices [3], [4], [5]. It results in the focusing of the manufactures of power converters on the algorithms, which increase energy efficiency, and on the proper tuning of control systems, which demands precise information on parameters of the objects under control [6]. Furthermore, a significant amount of motor drives involves sensorless control algorithms, which performance is sensitive to uncertainty of system parameters. They can significantly decrease the efficiency of a whole motor drive, operating with inaccurate parameters.

A conventional approach to tuning of control systems is the usage of predefined constants, which is simple in implementation, but does not take motor drive parameters variation into account [7]. As a result, a conventional approach has limited usage, therefore high-efficient motor drives involve other techniques, which consider change of motor parameters. The problem with the proper tuning of control systems is especially crucial in self-commissioning motor drives, which control motors with previously unknown values of parameters and have to estimate them at the stage of tuning [8], [9].

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As a result, estimation of system parameters has become an important topic, which attracts numerous researchers.

The stator phase resistance and inverter voltage drop are the most important parameters for motor drives, which frequently start or operate at low speeds. Precise estimation of the stator resistance improves the performance of non-injective position and speed estimators, especially in low-speed regions, where back-EMF is insignificant [10]. In turn, it makes short open-loop starting and fast closing of the control system possible, thus increasing the drive efficiency [11], [12].

Other important and challenging tasks, which requires precise information on stator resistance and inverter voltage drop, are motor fault detection, efficiency evaluation and monitoring of temperature [13], [14]. The temperature of the motor and inverter can be estimated using variation of a conductor resistance with the temperature [15], [16], [17]:

$$R = R_0 \left(1 + \alpha \left(T - T_0\right)\right), \tag{1}$$

where $R_0$ is a conductor resistance at the temperature $T_0$, $R$ is that resistance at the temperature $T$ and $\alpha$ is the temperature coefficient. It is $3.93 \cdot 10^{-3}$ 1/°C and $4.31 \cdot 10^{-3}$ 1/°C for pure copper and aluminum respectively, and is slightly higher for impure materials. At the same time the stator resistance may be a part of more complicated thermal models of motors. As it can be seen from (1), the resistance rises with the increase of temperature, however this raise is insignificant. Therefore, in order to obtain temperature with adequate error, the value of resistance must be estimated precisely.

The algorithms for system parameters estimation can be divided into online and offline techniques by the type of operation. Online techniques run in parallel to operation of motor drive, continuously estimating its parameters. They can detect change of parameters faster, so the system may tune online, keeping operation at high efficiency. These methods are suitable for drives with long continuous operation, where motor parameters significantly vary [18]. At the same time, implementation and adjustment of such techniques is a challenging task, which requires time and qualified engineers. Moreover, online methods typically demand powerful microcontrollers, thus their usage in low-cost systems is limited.

Simultaneously, the offline methods do measurements and estimate system parameters prior to the main working cycle of motor drives. The main disadvantage of this approach is the inability to track motor parameters variation during operation of the drive, therefore the estimated data reflect motor drive state before starting of the operation. However, system parameters may significantly vary during operation, especially in the drives with long running cycles. As a result, offline techniques are suitable for drives with short working cycles, where the estimated motor parameters do not change significantly. These techniques perfectly fit the requirements of motor drives performing in start/stop modes, e.g., washing machines drives, drives of lifting mechanisms, etc. The offline techniques are typically simpler than online methods and do not require qualified engineers and complicated tuning.

The purpose of this work was development of the algorithm capable to estimate stator resistance and inverter voltage drop in low-cost electric drive for dishwashers. This drive operates at short working cycles with frequent restarts and reverses. Considering this specific type of operation, the offline methods are the most convenient solution, which combines simple implementation and ease of tuning.

Therefore, this work proposes an offline method for measurement of stator resistance and inverter voltage drop, which injects DC current of different levels and estimates the desired parameters using least squares method (LSM). The paper considers traps and pitfalls in the estimation process, suggests measures to avoid them. The manuscript analyses impact of algorithm parameters variation on the tolerance of estimation and provides recommendation on their selection depending on the project requirements. The developed algorithm improved starting performance of the dishwasher sensorless motor drive and provided stable starting at different motor temperatures. After internal evaluation, the developed motor drive was put into mass production.

## II. STATE OF THE ART

In order to estimate stator resistance, a number of techniques were proposed. They mainly considered permanent magnet synchronous motors (PMSM) and induction motors (IM) [19], however they can be modified for operation with motors of other types.

The authors of [19], [20], [21], [22], [23], [24], [25], [26], [27], and [28] proposed various online techniques for the stator resistance estimation of induction motors, while the algorithms proposed in [20] and [21] involved various estimators. The work reported in [20] suggested a simpler estimating technique, capable to work online. The researches published in [22] and [23] considered the use of a model reference adaptive system (MRAS)-based technique for measurements in motors operating under deadbeat control and direct torque control (DTC). The authors of [24] and [25] proposed adaptive observers and studied their stable operation. The methods published in [26] and [27] suggested various injection-based algorithms, where [26] adapted its application at zero speeds. The research published in [28] involved artificial neural networks (ANN) for the estimation of resistance and demonstrated high tolerance of estimation.

The methods proposed in [15], [16], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], and [40] were developed for the online estimation stator resistance of PM synchronous motors. The techniques reported in [29], [30], [31], [32], and [33] suggested several estimators, where [30] studied adaptive estimator and algorithm considering machine saturation. The algorithms published in [32] and [33] proposed estimators of resistance for DTC systems and the research published in [31] suggested estimator, which is based on analysis of higher harmonics of back-EMF. The authors of [16], [34], and [35] adapted MRAS-based techniques and nonlinear Luenberger observer, capable to operate online. Several interesting techniques were reported recently in [36], [37], and [38], where the paper [36] involved quantum genetic algorithm and the authors of [37] and [38] proposed the usage of electrical signals affine projection of motors. The method published in [39] was designed for control systems of open-end winding motors, where the estimation technique defines motor resistance and PM flux linkage.

Simultaneously, the group of algorithms reported in [17] and [40] proposed various injection-based techniques, where paper [17] suggested a method for precise estimation of motor resistance for temperature estimation, and the authors of [40] recommended injections of current along $d$ and $q$ axes, optimizing for offline and online operations.

All above-mentioned algorithms are designed for online operation and estimate motor resistance with different errors, however they are difficult in tuning and implementation. Moreover, some of them are not applicable for operation at low speeds.

For the purpose of simplification of estimation algorithm and decrease of its development time, it is recommended to use offline techniques. The offline approaches are unable to detect changes of the stator resistance when motor operates, however it may not be necessary for several groups of applications. Therefore, offline estimation of motor resistance is attractive research area, where various researchers contribute and report their ideas [41], [42], [43], [44], [45].

The authors of [41] proposed injection of a high-frequency short time pulses simultaneously with avoiding of dead-time effect, however this method is hard in implementation and tuning. A good alternative to injection of signals was suggested in [42], where, in order to estimate every motor parameter, the authors changed the structure of the current controller and sought the minimum point of the current norm, based on a hill-climbing algorithm. This algorithm is easier in implementation, however is far from simplicity. Another work reported in [43], studied the impact of the sequence of parameter estimation on their errors and proposed the optimal identification sequence.

The authors of [44] proposed offline methods for low-error measurement of induction motor parameters, however this algorithm requires laboratory equipment and is not applicable in self-commissioning motor drives. For solving this problem, the paper [45] recommended a simple method developed for induction drives with self-commissioning feature, which uses injection of DC signals. It can measure resistance of the stator, however it is unable to estimate inverter voltage. Moreover, the authors did not provide recommendations on algorithm tuning and parameter selection, which decreases its applicability.

A simple approach for offline estimation of stator resistance was proposed in [46], where the author approximate voltage current characteristic of a motor drive with a first order polynomial using measurements in two points. The gain of this polynomial is total resistance of motor drive, which depends on the motor winding connection, therefore knowing this commanded connection, the phase resistance may be found. This approach is relatively fast and simple, however

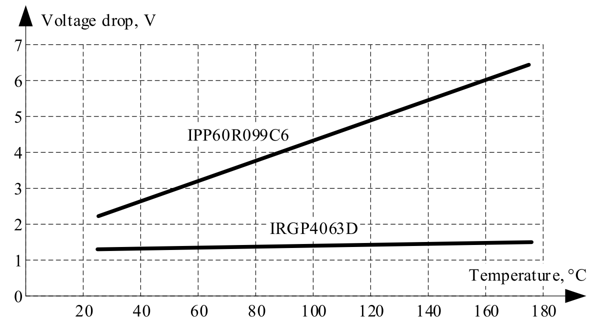


**FIGURE 1.** On-state voltage drop vs. temperature at 25 A.

is sensitive to measurement errors, therefore resistance estimation error may be high.

Simultaneously, the estimation of inverter voltage drop does not attract a lot of attention and only a few papers on this problem were published recently. The research published in [47] studied the inverter non-linearities and compensation methods; after that it suggested a technique for estimation of the inverter voltage drop, however this algorithm requires value of motor resistance. Furthermore, it operates with predefined constants and does not consider resistance variation, which results in higher errors.

Another method proposed in [48] considered compensation algorithms as well, however suggested the usage of predefined constants as values of voltage drops, which did not take their variation with a temperature into account and may decrease total performance of the motor drive.

The techniques similar to [48] suppose that the voltage drops across semiconductor devices are constants, which can be found in datasheets. However, the voltage drops vary, depending on the temperature and considering them to be constants, worsens the performance. It is illustrated by Fig. 1, which was taken from [49] and demonstrated variation of voltage drop with the temperature for two transistors operating at the same current density. This figure shows the characteristics of a trench IGBT IRGP4063D and super-junction MOSFET IPP60R099C6, and demonstrates that the voltage drop may be significant, therefore, has to be considered.

In order to compensate inverter's non-linearities and improve operation of sensorless estimators, the authors of [50] and [51] proposed detailed inverter model, which considers voltage drops across IGBT transistors and free-wheeling diodes, switching delays and dead-times. This approach significantly improved operation of self-commissioning drive, however have several disadvantages. The time of self-commissioning is long, which makes its execution before every motor's start impossible. Furthermore, this method does not take parameters variation with the temperature into account, so it can be recommended only for drives with relatively stable parameters.

The authors of [52] considered all possible current paths in inverter depending on the state of its switches and explained which voltage drop (transistor or diode) and sign should be used for compensation. It allows to compensate inverter

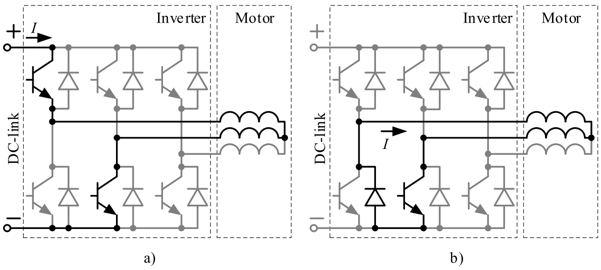


**FIGURE 2.** **Current paths a) energising; b) deenergizing.**

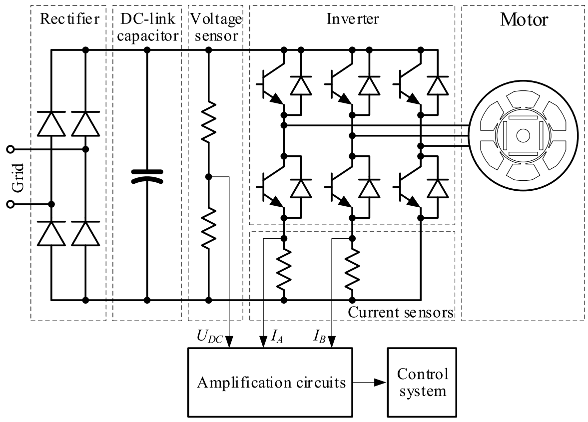


**FIGURE 3.** **Structure of electical drive.**

voltage drops precisely in all modes of operation and provides better performance, especially at low-speeds [53], [54].

In this research the authors focused on the typical drive operation in motor mode, with current paths demonstrated in Fig. 2. The deenergizing path is shown through the negative rail of the DC-link, however it can be implemented through the positive rail as well. The information on stator resistance and voltage drop is extremely important at low speeds, where the rotor back-EMF is low and impact of these parameters is significant. The control system in this mode of operation applies small voltages to the stator and most of the time phase current flows through two inverter switches or one switch and free-wheeling diode. The same situation occurs when the equivalent resistance is measured during standstill at low voltage; therefore, it was found that these operation modes can be considered to be similar.

After considering the existing offline techniques and analysis of their pros and cons, it was concluded that they were either too complicated, or did not guarantee enough precision. Thus, the necessity of the development of a simple measurement algorithm operating offline was detected. Therefore, this paper proposes such algorithm for measurement of stator resistance and inverter voltage drop, which combines simple implementation and provides low estimation errors.

## III. STRUCTURE OF DISHWASHER MOTOR DRIVE

The electric drives of dishwashers are low-cost systems, with the conventional structure used in various applications in automotive, home appliances, industry etc. They are intended for control of three phase Y-connected PM motors in the sensorless control mode and, therefore, do not include any position sensors. The electrical signals are measured by means of the DC-link voltage sensor and the motor phase current sensors, placed in two bottom legs of the inverter, Fig. 3. The phase voltages applied to the motor are calculated using commanded duty factors and sensed DC-link voltage, while two phase currents are measured in the conduction intervals of the corresponding switches and the third current is restored using Kirchhoff's law.

The control scheme of currently produced PMSM drives of dishwashers involves conventional field-oriented control scheme, enhanced with additional blocks for increasing efficiency. It contains two inner current loops in *dq* reference frames and outer speed loop, with proportional-integral (PI) type regulators, programmed according to [55]. The information on rotor position and speed, required for Park and Clarke transformations, is provided by the estimator, based on back-EMF prediction. The system is enhanced with an MTPA block, implemented as described in [56], [57], and [58], field-weakening algorithm and harmonics suppression techniques similar to those considered in [59]. In order to implement a number of control functions and service algorithms in a low-cost microprocessor, the math functions were optimized using assembler and special techniques considered in [60] and [61].

Taking into account that the dishwasher motor drive is a low-cost system, the new developing algorithm had to be simple and had no requirements to additional hardware, which might increase total cost. As a result, it had to be implemented as an enhancement of the software for described motor drive.

It should also be noted that due to the policy of cost optimization, the company planned usage of cheaper motor drives in future models of dishwashers. Thus, the inverter configuration with two current sensors will be substituted with one shunt current sensor in the DC-link, and the control system will be enhanced with current reconstruction algorithm. As a result, the inverter of the new configuration will provide lower precision in current measurements, therefore, the developing algorithm must be able to operate in that motor drive configuration as well.

## IV. PROPOSED ESTIMATION TECHNIQUE

The simplest technique for the offline estimation of stator resistance $R$ uses Ohm's law [62]:

$$R = \frac{U}{I}, \tag{2}$$

where $U$ is a voltage applied to the stator, and $I$ is the current in the stator windings. This approach is simple, however it does not take the inverter voltage drop into account, therefore, it works well only when the applied voltage is significantly higher than the voltage drop. At the same time, most of low- and middle-power electrical drives, including dishwasher motor drives, have motors with resistance in the range of 0.01 – 5 Ω, maximum current limitation of 1 – 100 A, and voltage drop across stator 1 – 15 V [63]. Simultaneously, the inverter voltage drop in power modules of the same power range,

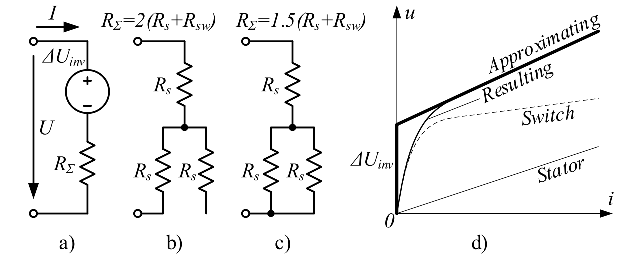


**FIGURE 4.** Measurement of the resistance a) Drive equivalent circuit; b), c) Possible connections of Y connected three-phase motors; d) Voltage-current characteristics.

is typically 1 – 6 V [64], thus these voltage drops are comparable and the inverter voltage drops may not be neglected. The better results can be obtained using [46], however this approximation method is sensitive to measurement errors, because it uses only two points. In order to improve precision of measurement without hardware modification, this paper proposes measurement of voltage current characteristic of motor drive in several points with the following approximation of the experimental data with first order polynomial using least squares.

For considering the inverter voltage drop, the electrical drive equivalent scheme is demonstrated in Fig. 4a, where $R_\Sigma$ stands for the motor equivalent resistance and $\Delta U_{inv}$ denotes the total inverter voltage drop across current path. The equivalent resistance depends on the connection of stator windings and can be equal either to $2\cdot(R_s + R_{sw})$ or $1.5\cdot(R_s + R_{sw})$, as demonstrated in Fig. 4b and c, where $R_s$ and $R_{sw}$ are stator and switch resistances, respectively.

After the equivalent resistance was estimated, the phase resistance $R_{ph} = (R_s + R_{sw})$ can be calculated and used in control processes. There is no necessity to segregate the exact value of $R_s$, because the inverter control system calculates phase voltages using measured DC-link voltage and commanded duty factors. Considering that switches are located after the voltage measurement point, control algorithms require total phase resistance $R_\Sigma$.

The inverter voltage drop $\Delta U_{inv}$ depends on the current path and in the proposed operational mode can be equal either to $2\cdot\Delta U_{sw}$ or $(\Delta U_{sw} + U_f)$, where $\Delta U_{sw}$ and $U_f$ are voltage drops across switch and free-wheeling diode respectively. These voltage drops differ, however the difference between them is about 10∼20%, thus they can be considered equal for the purpose of simplification. Despite inverter voltage drop decreases at low-currents (typically below 10% of the rated value), it can be considered a constant, because the operating modes of the overwhelming majority of motor drives are out of this range. Thus, the resulting and approximating voltage-current characteristics, which demonstrated in Fig. 4d, are used for parameter estimation.

Therefore, Ohm's law for the demonstrated equivalent circuit can be written as:

$$U = \Delta U_{inv} + IR_\Sigma. \tag{3}$$

As can be clearly seen from (3), it contains two unknown variables, therefore, it can not be used directly. In order to find

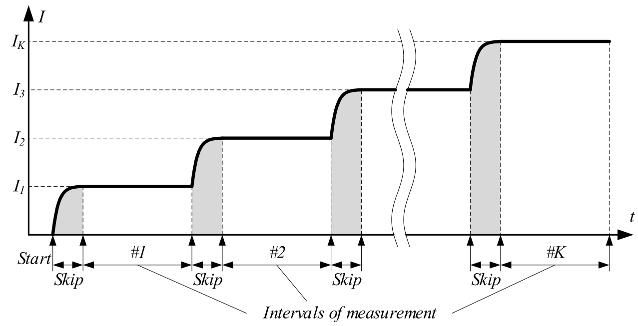


**FIGURE 5.** K-stepped resistance measurement.

$R_\Sigma$ and $\Delta U_{inv}$, the different levels of voltages $U_1, U_2, \ldots, U_k$ may be applied to stator, and corresponding currents have to be measured $I_1, I_2, \ldots, I_k$. as it is illustrated in Fig. 5. These data define a set of $k$ points: $(I_1, U_1,), (I_2, U_2, ) \ldots (I_k, U_k,)$, which can be approximated with the expected function (3), i.e. first order polynomial, using least squares, which corresponds to the conventional formulation of the problem [65], [66]. The gain and offset of the approximating line are equal to the estimated equivalent resistance of the motor $R_\Sigma$ and voltage drop across switches $\Delta U_{inv}$, respectively.

The approximation of set of experimental data with a first order polynomial is equal to solution of a system [69]:

$$\mathbf{AX} = \mathbf{B}, \tag{4}$$

where $\mathbf{X}$ is a vector with the coefficients of polynomial:

$$\mathbf{X} = \begin{vmatrix} \Delta U_{inv} \\ R_\Sigma \end{vmatrix}, \tag{5}$$

while $\mathbf{A}$ and $\mathbf{B}$ are matrixes:

$$\mathbf{A} = \begin{vmatrix} a_{00} & a_{01} \\ a_{10} & a_{11} \end{vmatrix} \mathbf{B} = \begin{vmatrix} b_0 \\ b_1 \end{vmatrix}, \tag{6}$$

which coefficients are defined as follows:

$$a_{00} = K;\, a_{10} = a_{01} = \sum_{i=1}^{K} I_i;\, a_{11} = \sum_{i=10}^{K} I_i^2$$
$$b_0 = \sum_{i=1}^{K} U_i;\, b_1 = \sum_{i=1}^{K} I_i U_i, \tag{7}$$

where $K$ is number of data points (number of steps), $U_i$ and $I_i$ are measured voltage and current at $i^{\text{th}}$ step, respectively.

Taking into account that the system (4) is second order, it can be easily solved analytically:

$$\begin{aligned} \mathbf{X} &= \begin{vmatrix} \Delta U_{inv} \\ R_\Sigma \end{vmatrix} = \mathbf{A}^{-1}\mathbf{B} \\ &= \left[ \mathbf{A}^{-1} = \frac{1}{a_{11}a_{00} - a_{01}a_{10}} \begin{vmatrix} a_{11} & -a_{01} \\ -a_{10} & a_{00} \end{vmatrix} \right] \\ &= \frac{1}{a_{11}a_{00} - a_{01}a_{10}} \begin{vmatrix} a_{11}b_0 - a_{01}b_1 \\ -a_{10}b_0 + a_{00}b_1 \end{vmatrix}, \end{aligned} \tag{8}$$

The stator winding configurations impact the total resistance $R_\Sigma$ as shown in Fig. 4b, c, thus, phase resistance $R_{ph}$

may be found as total resistance $R_\Sigma$, divided with the configuration gain. The inverter voltage drop is the total drop along the current path, therefore it has to be used without any modifications.

Despite the apparent simplicity of this method, its implementation has several traps and pitfalls, therefore they must be considered additionally.

### A. MEASUREMENT OF ELECTRICAL SIGNALS

The voltage of DC-link in most electrical drives supplied from standard grids is in the range of 300 – 500 V, depending on the number of input phases. At the same time, stator resistance and the maximum allowed stator current define voltage drop across windings, which is typically in the range of 1 – 15 V. Taking into account that inverter voltage drop is typically in the range of 1 – 6 V and varies, depending on operational conditions, it is hard to directly calculate the duty cycles for inverter switches, which can provide the desired current. In order to overcome this difficulty, a reversed approach has to be used. The desired value of current is commanded to the current controller, which controls inverter switches to provide the desired current, and the applied voltage is calculated by the measurement algorithm. A similar idea adapted for injection methods was reported in [17], where the inventers checked its performance and proved its superiority.

Another important point in the implementation of measurements is the necessity of strong filtering, caused by the high noise to signal ratio of the measured voltage. This can be done by averaging of the measured signals over relatively long periods of time:

$$U = \frac{1}{N}\sum_{j=1}^{N} u_j(t); \qquad I = \frac{1}{N}\sum_{j=1}^{N} i_j(t), \tag{9}$$

where $N$ is number of samples. As a result, (7) transforms into:

$$\begin{aligned}
a_{00} &= K; a_{10} = a_{01} = \frac{1}{N}\sum_{i=1}^{K}\sum_{j=1}^{N} i_{ji}(t);\\
a_{11} &= \frac{1}{N^2}\sum_{i=1}^{K}\left(\sum_{j=1}^{N} i_{ji}(t)\right)^2\\
b_0 &= \frac{1}{N}\sum_{i=1}^{K}\sum_{j=1}^{N} u_{ji}(t);\\
b_1 &= \frac{1}{N^2}\sum_{i=1}^{K}\left(\sum_{j=1}^{N} i_{ji}(t)\cdot\sum_{j=1}^{N} u_{ji}(t)\right),
\end{aligned} \tag{10}$$

### B. DEADTIME COMPENSATION

It was mentioned earlier that injection of DC current not exceeding maximum value, requires low voltage applied to a stator, thus, the deadtime impact is significant. Typical values of the deadtime in the range of 0.2 – 2 $\mu$s at 10 kHz PWM, distort the voltage applied to a stator at 0 – 2 % of the DC-link voltage value, which is 1 – 10 V. These numbers are comparable with the voltage drops across inverter switches and stator windings and may not be neglected. Therefore, in order to obtain precision and unbiased measurement results, the impact of deadtime must be eliminated.

The most challenging problem in deadtime compensation is operation in zones, where current is close to zero. It may cause various non-linear effects, which are hard to compensate precisely [67]. At the same time, the proposed algorithm uses unipolar current injection, which excludes the abovementioned problems. Therefore, the compensation of the deadtime may be implemented simply by addition of the constant voltage or by direct modification of the compare registers of PWM module at the value of deadtime (the sign of the modification depends on the current polarity).

Simultaneously, the developed motor drive also contained the deadtime compensation technique similar to the considered in [68]. In order to save the development time, the existing algorithm was involved.

### C. WINDING CONFIGURATION

In order to inject current into motors, the stator windings must form a closed path with the DC-link of the inverter. It can be done in several ways, depending on the motor stator configuration. For the most popular three phase motor with star connected windings and hidden neutral points, there are two possible configurations, Fig. 4b and c, where total stator resistance are equal to $2{\cdot}R_s$ and $1.5{\cdot}R_s$, respectively. The higher total resistance allows higher voltage to be applied to the stator without overcurrent, thus providing lower noise to signal ratio. Simultaneously, the phase connection demonstrated in Fig. 4b involves only two motor phases and leaves one phase unused, while the configuration demonstrated in Fig. 4c uses all three phases. As a result, the second configuration, distributes current over three phases and provides more even heating of the motor. Furthermore, the total resistance of the configuration, which involves three phases, is less, thus the total amount of the released heat is lower. As a result, motor parts temperature variation in heating cycle is lower, thus the total lifetime of the system increases. These specifics of the proposed technique must be considered, when the connection of stator windings is selected.

### D. ELECTRICAL TRANSIENTS

One of the important points, which must be considered, is electrical transients, where electrical signals are not stable and which have to be excluded from the samplings. These transients occur, when a next command of current is sent to current controller, which is illustrated by the greyed regions in Fig. 5. The transients character depends on system parameters and settings of current controller, and their typical length is about 1 – 100 ms.

Therefore, the control system must skip the time of transients from the measurements, which can be done in several

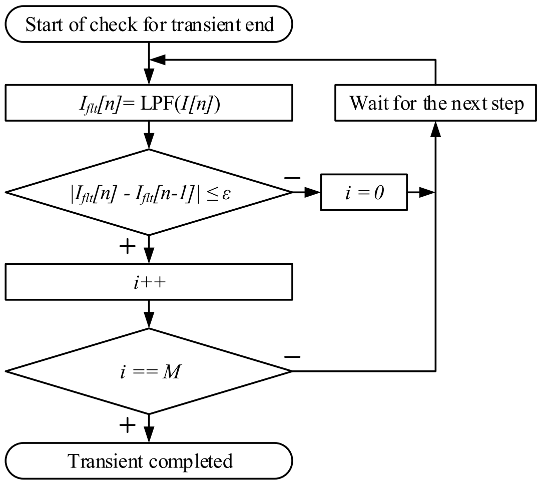


**FIGURE 6.** End of transient verification.

ways. The simplest approach is the usage of predefined fixed time, where the measurements are not performed. This time has to be selected as maximum possible length of transients in the motor drive. Despite the simplicity of this approach, it significantly increases total estimation time, because the skipping interval has to be equal to the maximum possible transient time and may significantly exceed real length of transients.

The better method for skipping the transients must analyze current signal and detect the moment of time, when the injected current is relatively stable. A simple algorithm of this kind is demonstrated in Fig. 6, where the input current is filtered by a low-pass filter (LPF) and analyzed for stability. The condition of stability is current variation lower than $\varepsilon$ during $M$ consecutive sampling periods, where $\varepsilon$ and $M$ are predefined constants.

### E. MECHANICAL TRANSIENTS

Another important point which has to be considered, is the initial positioning of the rotor, which occurs at the first injection step of DC current. When the resistance estimation is started, the position of the rotor is not known and is defined by the previous stoppage. However, there is a high probability that the direction of rotor magnetic field differs from the stator field created by the injected DC current, and forces the rotor to rotate and align along the stator field. In turn, when the rotor moves, its magnetic field creates a back-EMF in stator windings and distort phase current. As a result, the system has to wait until the end of rotor alignment before starting measurements.

The mechanical transients are typically slower than the electrical ones and last about 0.1 – 1 s, therefore this time has to be skipped from the measurement time at the first injection step.

### F. SELECTION OF ALGORITHM PARAMETERS

The performance of the developed technique significantly depends on the choice of its settings: number of injection steps $K$, current levels at those steps $I_1, I_2, \ldots, I_k$ and number of samples at each step $N$.

The number of injection steps defines a set of points for the approximation with a first order polynomial, thus the higher this number, the lower the error. However, significant increase of this number is meaningless, because it increases the measurement time, while error decrease is marginal. The purpose of the experimental part of this work is to define the optimal number of steps, depending on the precision required.

The commanded injected current defines noise to signal ratio: the lower the ratio corresponds to the higher injected current. Thus, according to this relation, it is desirable to increase the commanded current as high as possible. However, the difference between commanded currents defines approximation conditionality: the higher conditionality corresponds to the higher difference [69]. Therefore, from this point of view, it is desired to command current levels from zero to maximum current, with equal intervals. Therefore, the choice of commanded currents for injection is a trade-off between the measurement quality and the approximation conditionality.

The samples number $N$ used for averaging of the measured electrical signals impacts the quality of filtering: the higher the number, the lower the measurement error. However, significant increase of this number is meaningless, because it increases the measurement time, while the error decrease is marginal. Thus, the choice of number $N$ is a trade-off between measurement errors and speed of approximation. The purpose of the experimental part of this work is to define the optimal number $N$, depending on the precision required.

Considering the specifics of the developed algorithm discussed above, the technique flowchart is demonstrated in Fig. 7. It contains blocks for skipping the periods of transient and measured signals filtering, as explained above. Taking into account that the proposed technique injects DC currents, it simultaneously performs initial positioning of the rotor, thus, at the end of the estimation there are two options: the inverter either could be turned off, or the motor can start.

At this stage of theory development, it is difficult to formulate suggestions on the parameter selection for the proposed technique. Therefore, they will be provided after carrying out a series of tests. They are explained in the experimental part of this manuscript and suggestions on parameter selection are given.

## V. EXPERIMENTAL SETUP

The test jig used for the tuning of the proposed technique and analysis of impact of its parameter variation to estimation error, is demonstrated in Fig. 8. It includes stator and rotor of a multi-purpose commercial type PMSM which are assembled in special brackets and mounted on rails. It was designed and optimized as considered in [70] and [71] and its parameters are shown in Table 1. The motor is coupled with a Magtrol hysteresis brake BHB-3 and Magtrol speed/torque sensor TM 310/011, which did not take part in estimation and simply increased the moment of inertia. The measured signals were

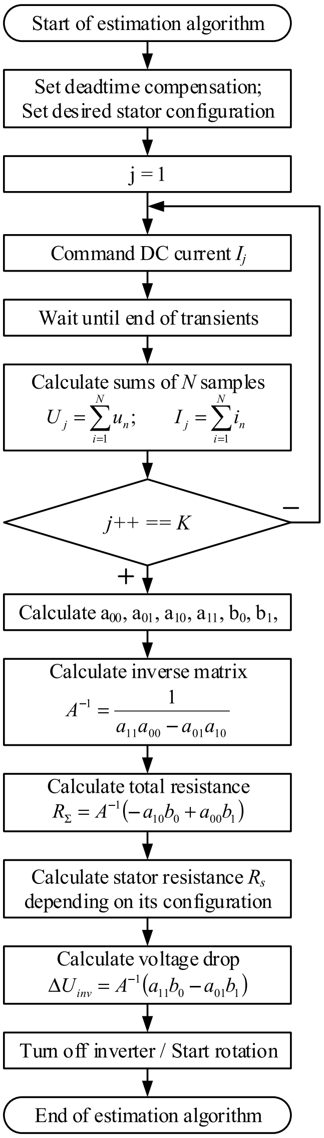


**FIGURE 7.** Proposed algorithm.

**TABLE 1.** Motor parameters.

| Parameter | Value |
|---|---|
| Number of poles pairs | P = 1 |
| Rated power, W | 100 |
| Rated current, A | 3 |
| Phase resistance, Ω | 4.21 |
| *d*-axis inductance, mH | 34 |
| *q*-axis inductance, mH | 42 |
| Back-EMF constant, V·s/rad | 0.07 |

captured by means of a Yokogawa DL-850 oscilloscope, capable of operating with raw data and pictures.

The inverter used in these experiments was designed especially for laboratorial experiments and researches. It was based on the commercial type inverter, designed to operate in 220 V (50 – 60) Hz standard grids, and included all its

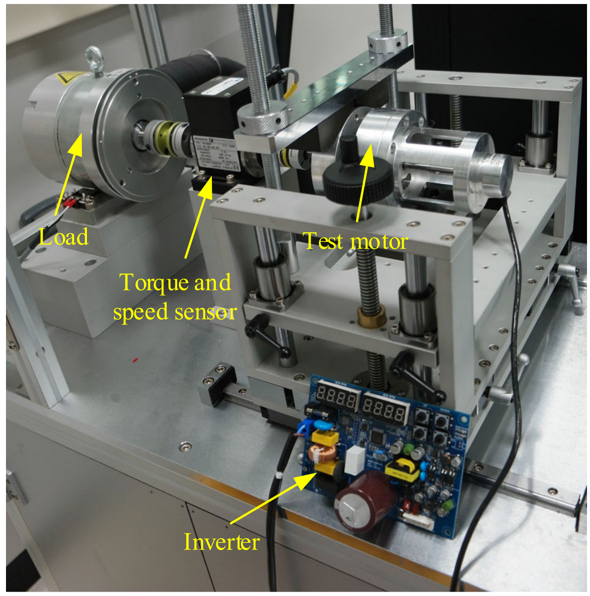


**FIGURE 8.** Experimental setup.

circuits. However, it was enhanced with additional interfaces necessary for researchers. The power module used to control the motors was the IM231-L6S1B (6 A/600 V) intelligent power module from Infineon, proposed for high-efficiency and low-cost applications. The structure of the inverter used in the experiments was similar to that demonstrated in Fig. 3 and additionally, included control buttons and displays as can be seen from Fig. 8.

The control system of the inverter was based on the Cortex M3 core iHart i910 microcontroller operating at 80 MHz, which operated the switches of power module at 8 kHz and sampled signals each 125 $\mu$s. Current and voltage sensors are implemented using measurement and shunt resistors with the tolerance of 1%. The signals from sensors initially passed the built-in amplifiers and after that, were digitalized by a 12-bit internal ADC. The inverter was enhanced with an interface to position encoder [72], [73] and communication circuits necessary for interaction with a PC, which was used for monitoring of internal data, and managing the control program.

## VI. EXPERIMENTAL RESULTS

The proposed technique was implemented as an additional routine of the standard control system of a commercial type motor drive for dishwashers, which was discussed earlier. The stator windings in all experiments were configured as shown in Fig. 4b ($R_\Sigma = 2{\cdot}R_s$), which provided lower noise to signal ratio. Simultaneously, for providing of even load distribution between motor drive phases, the one phase, which did not conduct current was selected randomly, using noise from the ADC. Since current control is performed for phase currents, the control system involves only one current controller, which operates in motor natural coordinates (*abc* reference frame).

Considering that the length of DC current injections was short, however the number of injections was significant, the

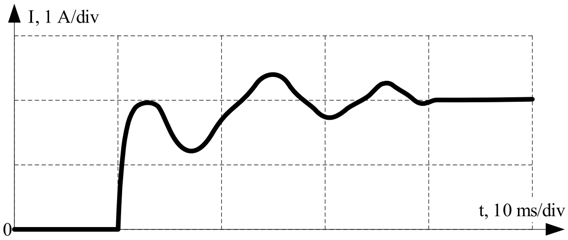


**FIGURE 9.** Current transient due to rotor rotation.

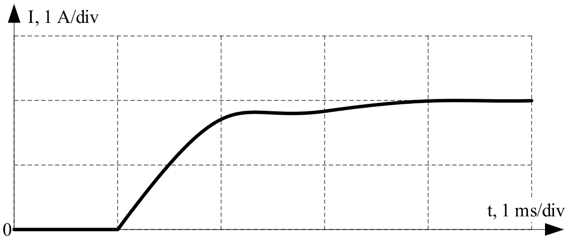


**FIGURE 10.** Current rise to 2 A.

inverter and motor might heat and distort measurements. In order to increase precision of the measurements, the motor drive was cooled with a fan and the temperature of inverter and motor was controlled to not exceed 30°C, when the ambient temperature was 25°C.

In order to exclude the impact of inverter dead-time on the results, the dead-time compensation algorithm with direct modification of the compare values was involved.

### A. TRANSIENTS

In order to demonstrate the mechanical and electrical transients which occur at injection of DC current, several experiments were conducted. In the first experiment, the rotor was manually unaligned with a stator field produced by injected DC current. After that, the commanded current was set to 2 A and current waveform was recorded and demonstrated in Fig. 9. It can be clearly seen that rotor oscillations induced back-EMF in motor windings, and distorted the current. This mechanical transient lasted about 30 ms, thus, this value must be considered for delay of measurements, after the first current level was commanded. However, there is no need in the usage of such delays, if an algorithm for the detection of end of current transient is involved.

The second experiment illustrates electrical transient, when the new current level was commanded. In order to exclude the impact of rotating rotor, it was initially set along the direction of stator field by short injection of the DC current. After that, the commanded current was set to 2 A and current waveform was recorded and demonstrated in Fig. 10. It should be noted that motor drive parameters are initially unknown and only their ranges are specified in the estimation algorithm. Therefore, in order to guarantee stability of operation, the gains of stator current controllers were calculated for the lowest possible motor parameters. As a result, the transients are slow and have aperiodic character, which can be clearly seen in Fig. 10. This electrical transient lasted about 3 ms, thus, this value must be considered for delay of measurements after a new current level was commanded.

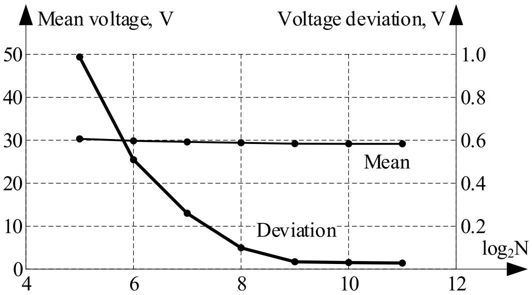


**FIGURE 11.** Mean voltage with deviation at different number of samples.

**TABLE 2.** Voltage measurement.

| Value | Number of samples | | | | | | |
|---|---|---|---|---|---|---|---|
| | 32 | 64 | 128 | 256 | 512 | 1024 | 2048 |
| Mean voltage, V | 30.33 | 29.86 | 29.63 | 29.41 | 29.21 | 29.18 | 29.18 |
| Deviation, V | 0.988 | 0.510 | 0.260 | 0.100 | 0.035 | 0.031 | 0.028 |

However, there is no need in the usage of such delays, if an algorithm for the detection of end of current transient is involved.

### B. NUMBER OF SAMPLES

In order to find the optimal numbers of samples $N$ for averaging of each measuring signal, a series of experiments has been carried out. In these experiments, the rated current of 3 A was commanded and after end of transient, the voltage was measured and averaged over $N$ points. Considering that $N$ is used in divider, it was selected as a power of two, for substitution of the division with shift.

Taking into account that the measured voltage has significantly higher noise to signal ratio than the current, only this signal was used for the evaluation of measurements. The voltage measurements for each number of samples $N$ was repeated five times and then the voltage mean value and its standard deviation were calculated. These results were put in Table 2 and illustrated by Fig. 11.

It can be clearly seen that the optimal number of data points for averaging is equal to 512 or 1024, which significantly decreases voltage deviation. The further this number increases, it significantly increases the measurement time, while the decrease of deviation is marginal. Taking into account results of these experiments, the sampling number $N$ for next tests was selected as 1024.

### C. CURRENT LEVELS

In order to check the impact of current levels and their number on the measurement results, a series of experiments were carried out. Initially, a detailed current-voltage characteristic of the motor drive was obtained, Fig. 12. The current was commanded in the range of $0 \sim 3$ A with a step of 0.25 A, however considering that low-current region ($0 \sim 0.5$ A) is nonlinear, the distance between points there was decreased to 0.1 A to provide more details. The current and voltage measurements in each selected point were performed five times and then the mean values of those signals were used

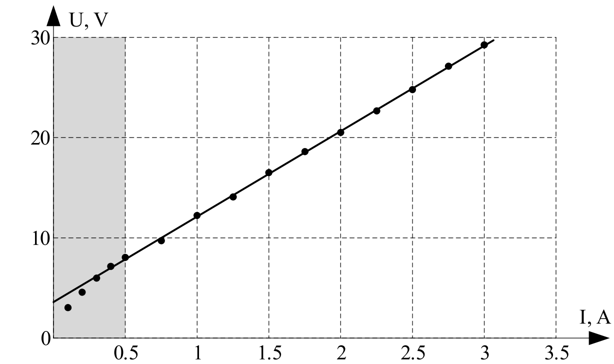


**FIGURE 12.** Current-voltage graph of the motor drive.

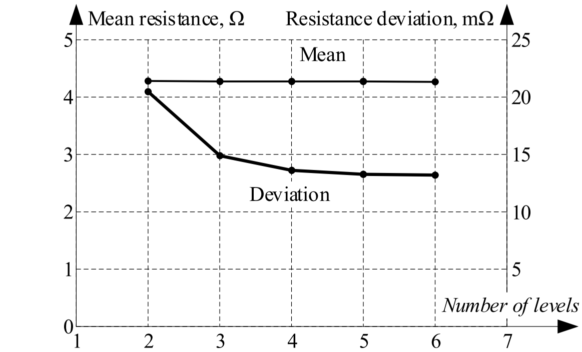


**FIGURE 13.** Mean stator estimated resistance with deviation.

**TABLE 3.** Resistance and inverter voltage drop.

| Value | Number of levels | | | | |
|---|---|---|---|---|---|
| | 2 | 3 | 4 | 5 | 6 |
| Mean resistance, Ω | 4.29 | 4.28 | 4.28 | 4.27 | 4.27 |
| Resistance deviation, mΩ | 21 | 15 | 14 | 13 | 13 |
| Mean drop of voltage, V | 3.49 | 3.55 | 3.53 | 3.51 | 3.50 |
| Deviation of voltage drop, mV | 254 | 147 | 130 | 117 | 117 |

for plotting. The data obtained, excluding the greyed region (0 ∼ 0.5 A) due to nonlinearities, were approximated using LSM with a first order polynomial.

The data in Fig. 12 demonstrates that the errors at low-currents are significantly higher than the errors at higher currents, thus it is preferable not to use low-current region. As a result, the lowest injection level of DC current was selected as 0.5 A, while the highest injection level was set to the rated current of 3 A. In the next experiments, the various numbers of the injected current levels were checked and the stator resistance and voltage drop across inverter switches were estimated. The experiment for each number of levels was repeated five times and mean values with deviations were calculated. The results obtained in these experiments are shown in Table 3 and demonstrated in Fig. 13 and Fig. 14. In order to illustrate operation of the proposed method, the oscillogram of the phase current for 3-level injection is demonstrated in Fig. 15.

It can be clearly seen that the increase in the number of injected levels results in significant increase of the precision

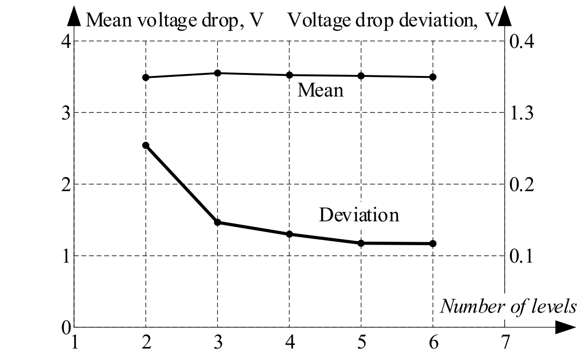


**FIGURE 14.** Mean estimated inverter voltage drop with deviation.

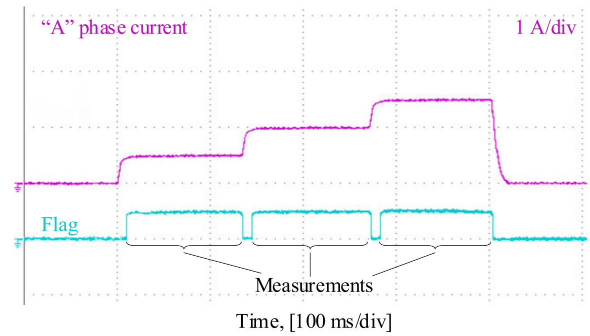


**FIGURE 15.** Injection of three current levels.

of estimation results, only until 3 ∼ 4 levels and after that, the measurement error decreases insignificantly. Therefore, it is recommended to inject 3 ∼ 4 levels of DC current, which is the compromise between precision and estimation speed.

In order to compare performance of the proposed method with the competitive algorithms, a number of experiments has been carried out and the results were put in Table 4. As it clearly seen, the proposed method is not the fastest one, however provides acceptable tolerance together with simplicity, which makes it the most convenient solution for low-cost motor drives.

## VII. DISCUSSION

The most important advantage of the developed algorithm is its simplicity and ease in tuning and implementation. Furthermore, it should be noted that proper current control provides stable injected DC currents, which average values are equal to the commanded current levels, and therefore, the measured currents may be substituted with the reference values, which simplifies calculations. If the $K$ commanded current levels are distributed evenly between the first $I_1$ and the last $I_k$ levels, the matrix elements in (7) can be pre-calculated. The $i$-th level of the injected current is:

$$I_i = I_1 + \frac{I_k - I_1}{K-1} i, \quad i = 0,\ 1,\ \ldots,\ K-1, \qquad (11)$$

therefore (7) transforms into:

$$a_{00} = K;$$

$$a_{10} = a_{01} = \sum_{i=0}^{K-1} \left( I_1 + \frac{I_k - I_1}{K-1} i \right) = \frac{I_k + I_1}{2} K$$

**TABLE 4. Comparison of various resistance estimation offline methods.**

| Method \ Characteristics | Estimation time, ms | Error, % | Complexity | Tuning | Additional equipment | Inverter voltage drop measurement | Inverter non-linearities |
|---|---|---|---|---|---|---|---|
| Short pulse injection [41] | 2~10 | 3.1 | Medium | Medium | No | No | Not considered |
| Seeking [42] | 600 | 2.0 | Medium | Medium | No | No | Not considered |
| Laboratory commissioning [44] | 300 | 1.0 | Complex | Complex | Yes | No | Not considered |
| IM self-commissioning [45] | 3000 | 20 | Simple | Simple | No | No | Considered |
| DC injection, 2 levels [46] | 300 | 2.1 | Simple | Simple | No | Yes | Considered |
| Proposed, 1024 points, 3 levels | 400 | 1.5 | Simple | Simple | No | Yes | Considered |

$$
\begin{aligned}
a_{11} &= \sum_{i=0}^{K-1} I_i^2 = \sum_{i=0}^{K-1}\left(I_1 + \frac{I_k - I_1}{K-1} i\right)^2 \\
&= \sum_{i=0}^{K-1}\left(I_1^2 + \frac{2I_1\left(I_k - I_1\right)}{K-1} i + \frac{\left(I_k - I_1\right)^2}{\left(K-1\right)^2} i^2\right) \\
&= \left[\sum_{i=0}^{K-1} i^2 = \frac{K\left(K-1\right)\left(2K-1\right)}{6}\right] \\
&= KI_1^2 + KI_1\left(I_k - I_1\right) + \frac{\left(I_k - I_1\right)^2}{\left(K-1\right)^2}\frac{K\left(K-1\right)\left(2K-1\right)}{6} \\
&= I_1 I_k K + \frac{\left(I_k - I_1\right)^2 K\left(2K-1\right)}{6\left(K-1\right)},
\end{aligned}
\tag{12}
$$

After that, the inverse matrix $\mathbf{A}^{-1}$ may also be easily calculated, which significantly simplifies online calculations.

At the same time, the proposed technique contains some traps and pitfalls, which must be carefully considered.

Injection of DC currents causes electrical and mechanical transients which may distort measurements, thus the time of transients must be excluded from measurements. It can be done using one of the proposed methods or involving new one. It should be noted, that the mechanical transients typically last ten times longer than the electrical transients, however they happen only at the first injection of a DC current, when the rotor might be unaligned.

The experimental results demonstrated that the selection of proper parameters significantly decreases measurement errors and improves stability of the estimations. Therefore, the developing drive should be carefully tested and the best combination of algorithm's parameters should be selected.

The inverter demonstrates non-linear behavior in the low-current region, however the model was obtained under assumption that the system is linear. Therefore, non-linear region should be identified and excluded from the measurements.

The rise in the number of injected levels of DC current increases precision of the estimation, however significant increase of these numbers is meaningless, because it enlarges estimation time and provides marginal improvements in quality. Practically, 3 – 4 injected levels are enough.

The same rule applies to the number of samples, which is used for averaging of the measured values. The higher this number, the lower the error. However, starting from some values, the error decrease is insignificant, and therefore it is meaningless to select higher numbers.

The developed technique injects DC currents and does not operate in transients, therefore it can work with motors of various types. Despite the fact that the most popular three phase star connected motor was used in this research, this approach can be easily extended to motors of other configurations, e.g., delta connected, open-end motors, etc.

The impact of the proposed algorithm on the system is negligible and mainly results in insignificant heating.

## VIII. CONCLUSION

This manuscript proposes a novel offline algorithm for measurement of motor phase resistance and voltage drop across inverter switches. In order to estimate these values, the developed technique consequently injects DC currents of various levels into the stator windings. After that, the data obtained at measurements is approximated with a first order polynomial using LSM, where gain of polynomial is the total stator resistance and its offset is equal to voltage drop. The main originality of the proposed method is usage of multi-level injection of current signals, which provide excessive data for calculation. Excessiveness of the data allows usage of the LSM, which increases the tolerance of curve fitting and hence decrease the error of parameters estimation.

The proposed algorithm was tuned, implemented and checked using commercial motor drives for dishwashers, however this technique may be used without serious modifications with motors of other types. Furthermore, its usage area is not limited to motors with three phase star-connected windings, and the proposed algorithm can be adapted for motors of other topologies.

In order to collect statistics for analysis and provide recommendation on the selection of parameters, a substantial number of experiments has been conducted. Based on these data, the authors suggested parameters for the measurement procedure, experimentally defined the optimal number of samples in each measurement and evaluated impact of the number of injection levels on the precision of the measurement results. They also considered some traps and pitfalls and suggested measures to avoid them. Finally, they proposed an optimization technique with precalculation of LSM matrix, which significantly simplifies calculations.

The proposed technique was highly evaluated and has been accepted for usage as a part of control systems of motor drives in mass-produced dishwashers.

## REFERENCES

[1] F. J. T. E. Ferreira and A. T. De Almeida, “Overview on energy saving opportunities in electric motor driven systems—Part 1: System efficiency improvement,” in *Proc. IEEE/IAS 52nd Ind. Commercial Power Syst. Tech. Conf.*, May 2016, pp. 1–8.

[2] A. T. De Almeida, F. J. T. E. Ferreira, and A. Q. Duarte, "Technical and economical considerations on super high-efficiency three-phase motors," *IEEE Trans. Ind. Appl.*, vol. 50, no. 2, pp. 1274–1285, Mar./Apr. 2014.
[3] V. Goman, V. Prakht, V. Kazakbaev, and V. Dmitrievskii, "Comparative study of induction motors of IE2, IE3 and IE4 efficiency classes in pump applications taking into account $CO_2$ emission intensity," *Appl. Sci.*, vol. 10, no. 23, p. 8536, Nov. 2020.
[4] A. Lukin, G. Demidova, A. Rassõlkin, D. Lukichev, T. Vaimann, and A. Anuchin, "Small Magnus wind turbine: Modeling approaches," *Appl. Sci.*, vol. 12, no. 4, p. 1884, Feb. 2022.
[5] V. Goman, V. Prakht, V. Kazakbaev, and V. Dmitrievskii, "Comparative study of energy consumption and $CO_2$ emissions of variable-speed electric drives with induction and synchronous reluctance motors in pump units," *Mathematics*, vol. 9, no. 21, p. 2679, 2021.
[6] M. N. Iqbal, L. Kutt, M. Lehtonen, R. J. Millar, V. Puvi, A. Rassõlkin, and G. L. Demidova, "Travel activity based stochastic modelling of load and charging state of electric vehicles," *Sustainability*, vol. 13, no. 3, p. 1550, Feb. 2021.
[7] S. J. Kim, J.-W. Kim, B.-G. Park, and D.-H. Lee, "A novel predictive direct torque control using an optimized PWM approach," *IEEE Trans. Ind. Appl.*, vol. 57, no. 3, pp. 2537–2546, May 2021.
[8] G. Pellegrino, B. Boazzo, and T. M. Jahns, "Plug-in direct-flux vector control of PM synchronous machine drives," *IEEE Trans. Ind. Appl.*, vol. 51, no. 5, pp. 3848–3857, Sep. 2015.
[9] G. Pellegrino, R. I. Bojoi, P. Guglielmi, and F. Cupertino, "Accurate inverter error compensation and related self-commissioning scheme in sensorless induction motor drives," *IEEE Trans. Ind. Appl.*, vol. 46, no. 5, pp. 1970–1978, Sep./Oct. 2010.
[10] A. Dianov, A. S. Anuchin, and V. F. Kozachenko, "Initial rotor position detection of PM motors," in *Proc. Power Electron. Motion Control Conf.*, 2004, pp. 1–6.
[11] A. Dianov, "Instant and seamless closing of control system of IPMSM after open-loop starting," in *Proc. 18th Int. Sci. Tech. Conf. Alternating Current Electric Drives (ACED)*, May 2021, pp. 1–6.
[12] A. Dianov, K. Young-Kwan, L. Sang-Joon, L. Sang-Taek, and Y. Tae-Ho, "Sensorless IPMSM based drive for reciprocating compressor," in *Proc. 13th Int. Power Electron. Motion Control Conf.*, Sep. 2008, pp. 1002–1008.
[13] K. Kudelina, T. Vaimann, B. Asad, A. Rassõlkin, A. Kallaste, and G. Demidova, "Trends and challenges in intelligent condition monitoring of electrical machines using machine learning," *Appl. Sci.*, vol. 11, no. 6, p. 2761, Mar. 2021.
[14] A. Rassolkin, T. Orosz, G. L. Demidova, V. Kuts, V. Rjabtsikov, T. Vaimann, and A. Kallaste, "Implementation of digital twins for electrical energy conversion systems in selected case studies," *Proc. Estonian Academy Sci.*, vol. 70, no. 1, pp. 19–39, 2021.
[15] S. D. Wilson, P. Stewart, and B. P. Taylor, "Methods of resistance estimation in permanent magnet synchronous motors for real-time thermal management," *IEEE Trans. Energy Convers.*, vol. 25, no. 3, pp. 698–707, Sep. 2010.
[16] S. S. Badini and V. Verma, "A new stator resistance estimation technique for vector-controlled PMSM drive," *IEEE Trans. Ind. Appl.*, vol. 56, no. 6, pp. 6536–6545, Nov. 2020.
[17] R. Antonello, L. Ortombina, F. Tinazzi, and M. Zigliotto, "Online stator resistance tracking for reluctance and interior permanent magnet synchronous motors," *IEEE Trans. Ind. Appl.*, vol. 54, no. 4, pp. 3405–3414, Jul./Aug. 2018.
[18] V. Goman, S. Oshurbekov, V. Kazakbaev, V. Prakht, and V. Dmitrievskii, "Energy efficiency analysis of fixed-speed pump drives with various types of motors," *Appl. Sci.*, vol. 9, p. 5295, Dec. 2019.
[19] C. Huang, L. Zhou, Z. Cao, and G. Yao, "Parameter identification of inverter-fed induction motors: A review," *Energies*, vol. 11, p. 2194, Aug. 2018.
[20] G. Kenné, R. S. Simo, F. Lamnabhi-Lagarrigue, A. Arzandé, and J. C. Vannier, "An online simplified rotor resistance estimator for induction motors," *IEEE Trans. Control Syst. Technol.*, vol. 18, no. 5, pp. 1188–1194, Sep. 2010.
[21] T. G. Habetler, F. Profumo, G. Griva, M. Pastorelli, and A. Bettini, "Stator resistance tuning in a stator-flux field-oriented drive using an instantaneous hybrid flux estimator," *IEEE Trans. Power Electron.*, vol. 13, no. 1, pp. 125–133, Jan. 1998.
[22] S. A. Davari, F. Wang, and R. M. Kennel, "Robust deadbeat control of an induction motor by stable MRAS speed and stator estimation," *IEEE Trans. Ind. Informat.*, vol. 14, no. 1, pp. 200–209, Jan. 2018.
[23] M. H. Holakooie, M. Ojaghi, and A. Taheri, "Direct torque control of six-phase induction motor with a novel MRAS-based stator resistance estimator," *IEEE Trans. Ind. Electron.*, vol. 65, no. 10, pp. 7685–7696, Oct. 2018.
[24] C. Luo, B. Wang, Y. Yu, C. Chen, Z. Huo, and D. Xu, "Decoupled stator resistance estimation for speed-sensorless induction motor drives considering speed and load torque variations," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 8, no. 2, pp. 1193–1207, Jun. 2020.
[25] M. S. Zaky, "Stability analysis of speed and stator resistance estimators for sensorless induction motor drives," *IEEE Trans. Ind. Electron.*, vol. 59, no. 2, pp. 858–870, Feb. 2012.
[26] S.-H. Lee, A. Yoo, H.-J. Lee, Y.-D. Yoon, and B.-M. Han, "Identification of induction motor parameters at standstill based on integral calculation," *IEEE Trans. Ind. Appl.*, vol. 53, no. 3, pp. 2130–2139, May/Jun. 2017.
[27] A. Hasanzadeh, D. M. Reed, and H. F. Hofmann, "Rotor resistance estimation for induction machines using carrier signal injection with minimized torque ripple," *IEEE Trans. Energy Convers.*, vol. 34, no. 2, pp. 942–951, Jun. 2019.
[28] B. Karanayil, M. F. Rahman, and C. Grantham, "Online stator and rotor resistance estimation scheme using artificial neural networks for vector controlled speed sensorless induction motor drive," *IEEE Trans. Ind. Electron.*, vol. 54, no. 1, pp. 167–176, Feb. 2007.
[29] Y. Xu, N. Parspour, and U. Vollmer, "Torque ripple minimization using online estimation of the stator resistances with consideration of magnetic saturation," *IEEE Trans. Ind. Electron.*, vol. 61, no. 9, pp. 5105–5114, Sep. 2014.
[30] M. Rashed, P. F. A. MacConnell, A. F. Stronach, and P. Acarnley, "Sensorless indirect-rotor-field-orientation speed control of a permanent-magnet synchronous motor with stator-resistance estimation," *IEEE Trans. Ind. Electron.*, vol. 54, no. 3, pp. 1664–1675, Jun. 2007.
[31] T. Wang, J. Huang, M. Ye, J. Chen, W. Kong, M. Kang, and M. Yu, "An EMF observer for PMSM sensorless drives adaptive to stator resistance and rotor flux linkage," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 7, no. 3, pp. 1899–1913, Sep. 2019.
[32] Y. Sangsefidi, S. Ziaeinejad, A. Mehrizi-Sani, H. Pairodin-Nabi, and A. Shoulaie, "Estimation of stator resistance in direct torque control synchronous motor drives," *IEEE Trans. Energy Convers.*, vol. 30, no. 2, pp. 626–634, Jun. 2015.
[33] Y. Sangsefidi, S. Ziaeinejad, and A. Mehrizi-Sani, "Sensorless speed control of synchronous motors: Analysis and mitigation of stator resistance error," *IEEE Trans. Energy Convers.*, vol. 31, no. 2, pp. 540–548, Jun. 2016.
[34] P. Bernard and L. Praly, "Estimation of position and resistance of a sensorless PMSM: A nonlinear Luenberger approach for a nonobservable system," *IEEE Trans. Autom. Control*, vol. 66, no. 2, pp. 481–496, Feb. 2021.
[35] O. C. Kivanc and S. B. Ozturk, "Sensorless PMSM drive based on stator feedforward voltage estimation improved with MRAS multiparameter estimation," *IEEE/ASME Trans. Mechatronics*, vol. 23, no. 3, pp. 1326–1337, Jun. 2018.
[36] K. Liu and Z.-Q. Zhu, "Quantum genetic algorithm-based parameter estimation of PMSM under variable speed control accounting for system identifiability and VSI nonlinearity," *IEEE Trans. Ind. Electron.*, vol. 62, no. 4, pp. 2363–2371, Apr. 2015.
[37] D. Q. Dang, M. S. Rafaq, H. H. Choi, and J.-W. Jung, "Online parameter estimation technique for adaptive control applications of interior PM synchronous motor drives," *IEEE Trans. Ind. Electron.*, vol. 63, no. 3, pp. 1438–1449, Mar. 2016.
[38] M. S. Rafaq, F. Mwasilu, J. Kim, H. H. Choi, and J.-W. Jung, "Online parameter identification for model-based sensorless control of interior permanent magnet synchronous machine," *IEEE Trans. Power Electron.*, vol. 32, no. 6, pp. 4631–4643, Jun. 2017.
[39] M. Pulvirenti, G. Scarcella, G. Scelba, A. Testa, and M. M. Harbaugh, "Online stator resistance and permanent magnet flux linkage identification on open-end winding PMSM drives," *IEEE Trans. Ind. Appl.*, vol. 55, no. 1, pp. 504–515, Jan. 2019.
[40] Q. Wang, G. Wang, N. Zhao, G. Zhang, Q. Cui, and D. Xu, "An impedance model-based multiparameter identification method of PMSM for both offline and online conditions," *IEEE Trans. Power Electron.*, vol. 36, no. 1, pp. 727–738, Jun. 2021.
[41] X. Wu, M. Lin, P. Wang, L. Jia, and X. Fu, "Off-line stator resistance identification for PMSM with pulse signal injection avoiding the dead-time effect," in *Proc. 22nd Int. Conf. Electr. Mach. Syst. (ICEMS)*, Aug. 2019, pp. 1–5.

[42] X. Ji and T. Noguchi, "Off-line parameter identification of interior permanent magnet motor by searching minimum point of current norm characteristics," in *Proc. Int. Symp. Power Electron., Electr. Drives, Autom. Motion*, Jun. 2014, pp. 279–284.
[43] J. Long, M. Yang, Y.-Q. Li, Y.-Y. Chen, and D.-G. Xu, "Parameter identification of permanent magnet synchronous motors: Sequence strategy comparative study," in *Proc. IEEE Transp. Electrific. Conf. Expo, Asia–Pacific*, Aug. 2017, pp. 1–6.
[44] T. Kostál, "Offline induction machine parameters identification suitable for self-commissioning," in *Proc. Int. Conf. Appl. Electron. (AE)*, Sep. 2017, pp. 1–4.
[45] D. Marcetic, V. Popovic, and P. Matic, "Simple procedure for self-commissioning of IM drive," in *Proc. Int. Symp. Ind. Electron. (INDEL)*, Nov. 2018, pp. 1–6.
[46] A. Dianov, "An algorithm for offline measurement of motor stator resistance and voltage drop across inverter switches for washing machine drives," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 10, no. 5, pp. 5798–5808, Oct. 2022.
[47] X. Wang, S. Nalakath, S. Filho, G. Zhao, Y. Sun, J. Wiseman, and A. Emadi, "A simple and effective compensation method for inverter nonlinearity," in *Proc. IEEE Transp. Electrific. Conf. Expo (ITEC)*, Jun. 2020, pp. 638–643.
[48] K. D. Hoang, Z. Q. Zhu, and M. P. Foster, "Influence and compensation of inverter voltage drop in direct torque-controlled four-switch three-phase PM brushless AC drives," *IEEE Trans. Power Electron.*, vol. 26, no. 8, pp. 2343–2357, Aug. 2011.
[49] International Rectifier. (2012). *Application Note AN-983, IGBT Characteristics*. [Online]. Available: https://www.infineon.com/dgdl/Infineon-IGBT_Characteristics-AN-v01_00-EN.pdf?fileId=5546d462533600a40153559f8d921224
[50] N. Bedetti, S. Calligaro, and R. Petrella, "Accurate modeling, compensation and self-commissioning of inverter voltage distortion for high-performance motor drives," in *Proc. IEEE Appl. Power Electron. Conf. Expo. (APEC)*, Mar. 2014, pp. 1550–1557.
[51] G. Pellegrino, P. Guglielmi, E. Armando, and R. I. Bojoi, "Self-commissioning algorithm for inverter nonlinearity compensation in sensorless induction motor drives," *IEEE Trans. Ind. Appl.*, vol. 46, no. 4, pp. 1416–1424, Jul./Aug. 2010.
[52] Y. Wang, W. Xie, X. Wang, and D. Gerling, "A precise voltage distortion compensation strategy for voltage source inverters," *IEEE Trans. Ind. Electron.*, vol. 65, no. 1, pp. 59–66, Jan. 2018.
[53] J. Lee, J. Yoo, and S.-K. Sul, "Stator resistance estimation using DC injection robust to inverter nonlinearity in induction motors," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Oct. 2020, pp. 2425–2430.
[54] S. Wei, Y. Yong, W. Gaolin, and X. Dianguo, "Accurate inverter error compensation using self-tuning stator current estimation error in sensorless induction motor drives," in *Proc. IEEE Ind. Appl. Soc. Annu. Meeting*, Oct. 2014, pp. 1–6.
[55] A. Anuchin, A. Dianov, and V. Kozachenko, "Adaptive efficient control for switch-reluctance drives with DCDC-regulator for inverter supply," in *Proc. Power Electron. Motion Control Conf.*, 2004, pp. 1–5.
[56] A. Dianov, N. S. Kim, and S. M. Lim, "Sensorless starting of horizontal axis washing machines with direct drive," in *Proc. Int. Conf. Electr. Mach. Syst. (ICEMS)*, Oct. 2013, pp. 1–6.
[57] A. Dianov, "Stoppage noise reduction of reciprocating compressors," *IEEE Trans. Ind. Appl.*, vol. 57, no. 5, pp. 4376–4384, Sep. 2021.
[58] A. Dianov, N. S. Kim, and S. M. Kim, "Sensorless starting of direct drive horizontal axis washing machines," *J. Int. Conf. Elect. Mach. Syst.*, vol. 3, no. 2, pp. 148–154, Apr. 2014.
[59] A. Dianov and S.-T. Lee, "Novel IPMSM drive for compact washing machine," in *Proc. 31st Int. Telecommun. Energy Conf.*, Oct. 2009, pp. 1–7.
[60] A. Dianov and A. Anuchin, "Review of fast square root calculation methods for fixed point microcontroller-based control systems of power electronics," *Int. J. Power Electron. Drive Syst.*, vol. 3, no. 11, pp. 1153–1164, 2020.
[61] A. Dianov and A. Anuchin, "Fast square root calculation for control systems of power electronics," in *Proc. 23rd Int. Conf. Electr. Mach. Syst. (ICEMS)*, Nov. 2020, pp. 1–6.
[62] H. Zhang, W. Wu, and L. Wang, "An improved off-line identification technology for parameters of surface permanent magnet synchronous motors," in *Proc. 20th Int. Conf. Electr. Mach. Syst. (ICEMS)*, Aug. 2017, pp. 1–4.
[63] A. Hughes and B. Drury, *Electric Motors and Drives*. Amsterdam, The Netherlands: Elsevier, 2013.
[64] R. W. Erickson and D. Maksimovic, *Fundamentals of Power Electronics*. Norwell, MA, USA: Kluwer Academic, 2004.
[65] P. R. Bevington and D. K. Robinson, *Data Reduction and Error Analysis for the Physical Sciences*. New York, NY, USA: McGraw-Hill, 1969.
[66] D. Alciatore and R. Miranda, *The Best Least-Square Line Fit*. Cambridge, MA, USA: Academic Press, 1995.
[67] A. Cichowski and J. Nieznanski, "Self-tuning dead-time compensation method for voltage-source inverters," *IEEE Power Electron Lett.*, vol. 3, no. 2, pp. 72–75, Jun. 2005.
[68] N. Urasaki, T. Senjyu, K. Uezato, and T. Funabashi, "Adaptive dead-time compensation strategy for permanent magnet synchronous motor drive," *IEEE Trans. Energy Conv.*, vol. 22, no. 2, pp. 271–280, Jun. 2007.
[69] V. Skala, "Least square method robustness of computations: What is not usually considered and taught," in *Proc. Federated Conf. Comput. Sci. Inf. Syst.*, Sep. 2017, pp. 537–541.
[70] V. Dmitrievskii, V. Prakht, and V. Kazakbaev, "IE5 energy-efficiency class synchronous reluctance motor with fractional slot winding," *IEEE Trans. Ind. Appl.*, vol. 55, no. 5, pp. 4676–4684, Sep. 2019.
[71] V. A. Dmitrievskii, V. A. Prakht, and V. M. Kazakbaev, "Ultra premium efficiency (IE5 energy-efficiency class) synchronous reluctance motor with fractional slot winding," in *Proc. 13th Int. Conf. Electr. Mach. (ICEM)*, Sep. 2018, pp. 1015–1020.
[72] A. Anuchin, A. Dianov, and F. Briz, "Synchronous constant elapsed time speed estimation using incremental encoders," *IEEE/ASME Trans. Mechtronics*, vol. 24, no. 4, pp. 1893–1901, Aug. 2019.
[73] A. Anuchin, A. Dianov, D. Shpak, V. Astakhova, and K. Fedorova, "Speed estimation algorithm with specified bandwidth for incremental position encoder," in *Proc. 17th Int. Conf. Mechatronics-Mechatronika*, 2016, pp. 1–6.

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