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Fuzzy Logic based Fault Detection of PMSM Stator Winding Short under Load Fluctuation using Negative Sequence Analysis

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Abstract— **A negative sequence analysis coupled with a fuzzy logic based approach is applied to fault detection of permanent magnet synchronous motors (PMSM). First, the fundamental components of the motor terminal currents and voltages are separated effectively, based on which the negative sequence components are calculated. A fuzzy logic based approach is implemented to generate a robust detection using the adjusted negative sequence current and negative sequence impedance. The adjusted negative sequence current is obtained by separating the high frequency components caused by the load fluctuation from the total negative sequence current. The adjusted negative sequence current provides a qualitative evaluation on severity of the stator fault. Validation of the method is performed online using a PMSM experimental setup with dSPACE® and Matlab®/Simulink® environment. The use of fuzzy logic improves the sensitivity of fault detection while reducing false alarm rate under load fluctuations.**

I. Introduction

Detection and diagnosis of faults in power systems is of great practical significance. Early detection of stator short circuit fault in permanent magnet synchronous motors (PMSM) is critical in preventing a major damage to the motor. Fast and accurate diagnosis of this type of faults allows adequate action time to protect the power system and the motor itself. Recently, there has been much interest in early fault detection and diagnosis techniques for condition based maintenance (CBM) [1-2]. This approach relies on information provided by condition monitoring systems to assess system condition continuously. The proposed technique in this work forms a basis for implementing CBM in a physical system.

In literature, much work on fault detection of electric machines is focused on induction motors, e.g., [3-5], and the references therein. Conversely, FDD research on permanent magnet (PM) motors is inadequate considering the growing application of PMSM in high performance systems, such as electrical vehicles and ship propulsion systems. The lack of publications in detection of stator winding circuit faults in PMSM prevents us from presenting a systematic comparison of the proposed method. However, recent success of using negative sequence as a detection indicator for induction motors, as presented in [3][6], may be extended as an approach to PMSM. In [6], a comparative analysis is provided for online detection of stator winding interturn short fault in induction motors. The authors compared several detection methods in terms of diagnostic efficiency and requirements for practical implementation. Among all the analyzed techniques, those based on the sequence components are considered the most promising. It is claimed in [6] that the negative sequence components present a high diagnostic efficiency based on the compensation of nonidealities, good experimental results and medium simplicity for practical implementation. While the negative sequence current is able to detect and diagnose a stator winding short, the method is unable to discriminate between an interturn short fault and the unbalance in the power supply, which is common in the operation of power systems. On the other hand, the negative sequence impedance is nearly independent of the unbalance supply, but it shows some deficiencies in the evaluation of fault severity because the motor and sensor asymmetries considerably decrease the sensitivity of this indicator [6].

Additionally, experiments with a PMSM testbed have shown a significant increase in the high frequency components in the negative sequence current under load fluctuation conditions. This behavior can trigger false alarms in conditioning monitoring systems under motor healthy operation. On the contrary, the negative sequence impedance has shown a weak dependency on a load change. The approach introduced in this work is fault detection for stator winding short circuit fault in a PMSM based on negative sequence components and fuzzy logic. Combining fuzzy logic with negative sequence analysis, the proposed method conquers the limitations of the negative sequence based fault detection approaches as mentioned above. The fault detection technique can not only differentiate between an asymmetry caused by a stator shorted turns and an unbalance due to load variations, but also provide a measure on the fault severity level. Although the effect of other sources of asymmetries, such as inherent motor unbalance and instrumentation asymmetry, is not considered in this paper, the threshold established experimentally under healthy conditions permits a real assessment of the motor condition.

The remainder of this paper is organized as follows: In section II, theoretical fundamentals of the proposed fault detection system are introduced, which covers both negative sequence analysis and the fuzzy logic method. Section III describes the experimental setup used in this fault detection development for PMSM. Then, the experimental results

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obtained from this testbed are presented in section IV. Finally, conclusions drawn from this study are given in section V.

II. METHODOLOGY

A. Negative Sequence Analysis

Asymmetries in the three phase quantities of PMSM may arise due to several reasons, such as interturn short circuit, inherent motor and instrumentation asymmetries, load fluctuations and unbalanced supply voltages. Such asymmetries can be reflected in negative sequence components. Both analytical and experimental results have demonstrated an increase in negative sequence current under a stator interturn short circuits [7]. However unbalanced supply voltage can produce similar asymmetry. Modifications to this approach have been proposed by Sottile and Kohler [3] to compensate the influence of voltage supply using the effective negative sequence impedance as a fault indicator. While the robustness has been improved with regard to unbalanced supply, negative sequence impedance presents some difficulties in evaluating the level of fault severity. The rest of this section reviews the established negative sequence analysis briefly, based on which the adjusted negative sequence current is proposed in order to generate robust fault detection under load fluctuation conditions.

The negative sequence current is obtained from the measurement of the three phase currents of PMSM using:

$$I_{a2} = \frac{1}{3}\left(I_{a,f} + \alpha^2 I_{b,f} + \alpha I_{c,f}\right) \tag{1}$$

where $I_{a,f}, I_{b,f}$ and $I_{c,f}$ are the magnitudes of the fundamental components of the three phases current signals, and α is a phase rotation operator equivalent to $e^{i2\pi/3}$ or 120°.

Similarly, the negative sequence voltage can be calculated as,

$$V_{a2} = \frac{1}{3}\left(V_{a,f} + \alpha^2 V_{b,f} + \alpha V_{c,f}\right) \tag{2}$$

where $V_{ab,f}, V_{bc,f}$ and $V_{ca,f}$ are the magnitudes of the fundamental components of the three phases voltage signals.

While the directly measurable voltages during experiments are usually phase to phase quantities, the phase to neutral voltages of the three phases can be obtained using (3).

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix}\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} \tag{3}$$

Then, by definition, the negative sequence impedance can be calculated according to (4) [6],

$$Z_{a2} = \frac{V_{a2}}{I_{a2}} \tag{4}$$

The value of negative sequence current quantitatively represents asymmetries coupled to a specific condition of an electrical system, in our case, the PMSM. Hence, a load fluctuation of frequency, f_{load}, produces a nonstationary asymmetry condition that yield a significant increase in the components of high frequency in the negative sequence current. As a result, a false alarm may arise in the condition monitoring system as illustrated in Fig. 1. This figure shows a series of different conditions in PMSM with stator fault, and/or load fluctuations. Clearly, for some healthy conditions with severe load fluctuations, the value of negative sequence current is even higher than that under fault conditions.

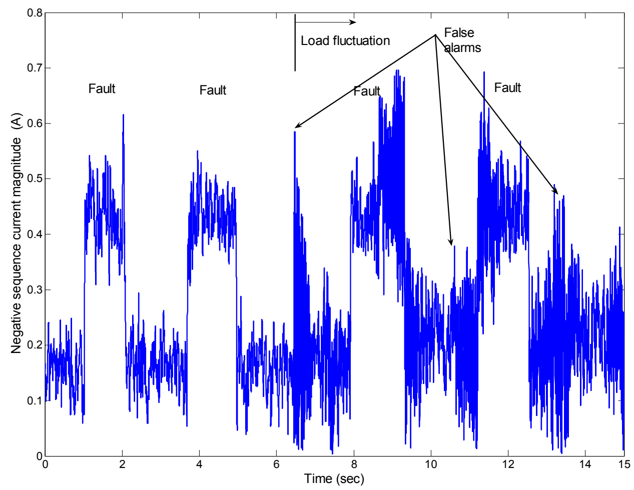

Fig. 1. Negative sequence current for unload and fault condition (0<t<6.5 *sec*) and load fluctuation and fault condition (t>6.5 *sec*).

From a signal point of view, the difference between the negative sequence current caused by a fault condition and that caused by load fluctuations is that they are associated with the particular domain of frequencies.

By separating the negative sequence current caused by the fault, including the inherent asymmetries of PMSM, and the load, one can get:

$$I_{a2} = I_{a2(fault)} + I_{a2(load)} \tag{5}$$

where I_{a2} is the actual value of negative sequence current obtained using (1).

Reliable online assessment of the fault condition implies the use of an indicator insensitive to uncertainties, i.e. robustness. To improve fault detection robustness, we need remove the component associated with the load fluctuation from the negative sequence current, which means:

$$I_{a2(fault)} = I_{a2(actual)} - I_{a2(load)} = I_{a2\ adjusted} \tag{6}$$

Therefore, the adjusted negative sequence current is determined by passing the negative sequence current through a 2nd order low pass *Butterworth* filter to remove the high frequency components produced by the load fluctuation.

Although using $I_{a2(fault)}$ and Z_{a2} independently is adequate to detect the fault condition under a constant load condition, it is insufficient to assess the actual condition of the motor under load fluctuations. In order to assess the motor's condition correctly, a heuristic interpretation is needed that can simultaneously evaluate the two values of negative sequence components. In this paper, we propose to use a fuzzy logic system, which is a simple method to quantitatively interpret and analyze the values of adjusted negative sequence current and negative sequence impedance under a specific operating condition.

B. Fuzzy Logic based Fault Detection

In recent years, fuzzy logic has been increasingly utilized in various applications. Fuzzy logic is an extension of multivalued logic based on the theory of fuzzy sets, which relates to classes of objects with unsharp boundaries and in which membership is a matter of degree. The basic of fuzzy logic are linguistic variables, whose values are words rather than numbers [9]. This characteristic gives to fuzzy logic some remarkable practical advantages in flexibility, tolerance to imprecise data, etc. A rule basis in fuzzy logic can be based on the experience of experts. In this case, the knowledge on the negative sequence components' behavior indicates the presence of a fault in PMSM.

The fuzzy logic systems provide a robust and sensitive detection. The detection process is accomplished using a fuzzy logic system with a fuzzy membership function module. This membership module provides a qualitative heuristic interpretation of the adjusted negative sequence current and the negative sequence impedance based on the expert knowledge. Trapezoidal membership function is used with approximately 25% overlap, which provides reasonable results in this experimental study. This initialization of the membership function is in accordance with [10]. These fuzzy heuristics serve to build the universe of discourse *X* and *Y* for each of the input spaces. They are represented in the standard notation used in [11]

$$X = \left[\mu_{low}\left(I_{a2}\right), \mu_{medium}\left(I_{a2}\right), \mu_{high}\left(I_{a2}\right)\right], I_{a2} \in X \tag{7}$$

$$Y = \left[\mu_{low}\left(Z_{a2}\right), \mu_{medium}\left(Z_{a2}\right), \mu_{high}\left(Z_{a2}\right)\right], Z_{a2} \in Y \tag{8}$$

where $\mu_i\left(\lambda\right)$ is the grade of membership of λ in $I=\{i \in I$ low, medium, high$\}$, $\lambda \in X, Y$. The universe of discourse represents the input's range of operation.

The fuzzy rule module provides the antecedent-consequence statements of fuzzy logic. These statements provide the condition of the fault being monitored given the linguistic operating range of inputs. The fuzzy rule represents a combination of the qualitative heuristic knowledge of the operating system and the quantitative description of the motor conditions [8]. The consequence provides the quantitative information about the motor using the descriptions of healthy (Normal) and fault (Alarm), as shown in Fig. 2. These conditional statements are based on combinations of the fuzzy membership function. For example,

If I_{a2} is high, *and* Z_{a2} is low, *then* the condition of the motor is fault.

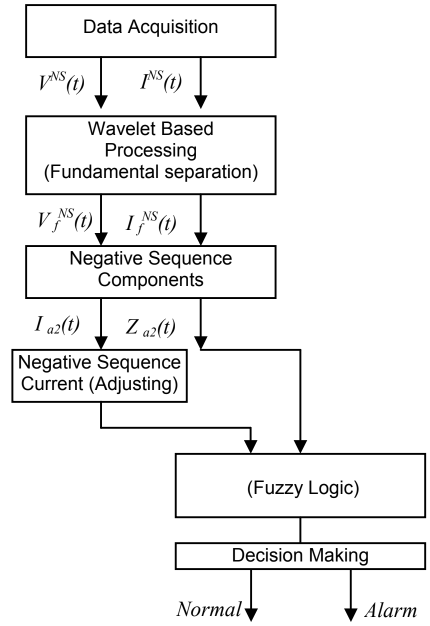

Fig. 2. Schematic diagram of the detection process

A starting point for the fuzzy rules is predetermined by the minimal knowledge available at design time. The qualitative heuristic knowledge about the input and the correct rules are obtained through experiments by running the PMSM under various conditions repetitively. The fuzzy inference engine is the Mamdani type. The defuzzificaton is achieved by the centroid method. The output of the fault detection system is zero for healthy condition and the adjusted negative sequence current for fault condition. In healthy condition, all asymmetries related to the motor inherent asymmetries and the instrumentation are taken into account experimentally, which provides a baseline of reference. The main feature of this fault detection system is its independency in evaluating the fault severity level and the load fluctuation condition. In this way, the proposed fault detection system effectively reduced fault alarm rate.

III. Experimental Approach

Experimental study of fault detection usually requires operating a physical system under some fault conditions, which may be dangerous, destructive, and costly. Efforts have been made in the lab to perform fault detection for PMSM experimentally. Fig. 3 is a picture of the testbed used in this work.

The system consists of a 28.8 *kVA* variable frequency drive connected to a bus supplying the power and control to a 11.25 *kW*, 640 *V*, 60 *Hz*, *Y*-connected, 8- pole PMSM. A dc motor is coupled with the PMSM mechanically served as a load to the PMSM. During the experiments, the load can be changed by varying the armature resistance of the dc motor. In order to emulate a load fluctuation condition, a torque reference is applied to the dc motor to produce load fluctuations, such as increasing or decreasing the load from 0% up to 30 or 45 % of the rated torque of PMSM.

Fig. 3 Completed electrical experimental setup.

In this proposed experimental setup, the PMSM is specifically designed for fault detection purpose, especially the stator winding faults. To imitate the fault conditions, the stator windings of the PMSM have been reconstructed. A schematic illustration of this reconstruction is shown in Fig. 4. The figure illustrates that the windings in one phase of the motor are equipped with several accessible taps so that a stator winding short fault of different severity can be introduced. A normally open switch was added between any two of the taps. The fault can then be initiated by momentarily closing this switch, causing a current flowing through the shorted path. A fuse is placed in series with the switch, which provides passive protection to the motor under the fault condition. This protection is proved necessary later because the fault current in our test turned out to be three to four times higher than the rated current of PMSM. The different level of fault conditions can be simulated by closing different pairs of taps, which can also be observed by monitoring the fault current generated in the shorted loop. Currently, only two caps are placed in phase *A* with the shorted windings of 6.25% and 12.5%, respectively. To emulate a less severer fault condition, an adjustable resistor has been used as shown in Fig. 4. Change of the severity level of the stator interturn short fault can be emulated by adjusting the value of this resistor, which then be reflected in the variation of the loop current [12] as shown in Table I.

The acquisition system is developed using Matlab/Simulink with dSPACE as an interface to the hardware, i.e. PMSM drive system. The algorithm is first developed in Matlab®/Simulink®. When it is verified in simulation, the model is compiled using Real Time Workshop (RTW®) and run in real time. The fully tested algorithm then is applied to the electrical system and performance can be studied. A dSPACE® based data acquisition system is used to display and record the three line voltages, the three line currents, the FDD output and the torque signal.

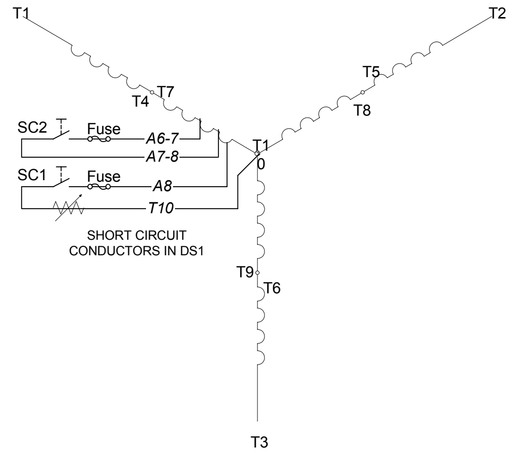

Fig. 4. Stator winding short circuit setup with external variable resistor

TABLE 1. VALUES OF LOOP CURRENT COMPARED WITH THE PERCENTAGE OF SHORTED WINDINGS IN PHASE A OF THE PMSM

Implementation	Loop Current (*A*)	Percentage of Shorted Windings (%)
Taps	115	12.5
	75	6.25
Variable resistor	65	6.25 % + R1
	41	6.25 % + R2
	25	6.25 % + R3

In the proposed fault detection system, the data acquisition allows sampling of three phase line voltages $V^{NS}(t)$ and currents $I^{NS}(t)$, where "NS" represent a nonstationary signal. The signals are sampled with a 2.5 *kHz* frequency and processed using wavelet db8 (Daubichie8) at 4 levels of decomposition to obtain the fundamental components of each phase, $V_f^{NS}(t)$ and $I_f^{NS}(t)$. This process introduces a delay of 0.2048 *sec* because of the buffer used in the wavelet analysis. $V_f^{NS}(t)$ and $I_f^{NS}(t)$ are then used to generate the negative sequence current indicator I_{a2} and the effective negative sequence impedance Z_{a2} according to (1) and (4).

IV. RESULTS

A series of tests are designed to demonstrate detectability of the emulated stator winding short circuit fault using the proposed system with and without load fluctuation.

A series of case studies are performed attempting to cover a wide variety of operating conditions of different fault and load level. However, due to the space limitations, only two typical cases are presented here. The cases have a fault loop current of 25 *A* and 41 *A* respectively, which representing a relatively small fault under different load fluctuations. The time window used in both experiments is 15 sec. In this time frame, faults are applied in variable intervals of time, covering healthy condition (baseline), fault without load and fault with load fluctuations. Values of the fault indicator at these conditions are compared. Experiments results are displayed in Fig. 4-7. The baseline in these figures is a normalized zero-valued output, corresponding to the healthy condition in the motor.

A. Case 1: Stator winding short with 25 A Loop current and 30% load variation

This experiment is performed to demonstrate detectability under a relatively small fault with 25 *A* loop current under load fluctuation conditions. During the first time interval from 0 to 6.3 *sec*, such a fault is applied under no load condition. Afterwards, a load fluctuation between 0-30% of the rated torque is introduced. Fig. 4 shows the value of negative sequence current obtained from this experiment. The load fluctuation brings the motor into a nonstationary condition so that the negative sequence current is affected noticeably producing spikes. Therefore, simply using the negative sequence current as a fault indicator can generate a false alarm in the fault detection system. The proposed fault detection method provides a solution to this problem. As shown in Fig. 5, the system is quite effective in distinguishing the healthy and fault condition under load fluctuation. Meanwhile, the adjusted negative sequence current, as a fault indicator, remains almost unchanged during the complete time of the test. This result demonstrates the fault indicator's robustness to the load fluctuation.

B. Case 2: Stator winding short with 41.5 A loop current and 45% load variation

Another experiment is carried out in similar conditions as case 1, but with a load fluctuation up to 45% of the rated torque and a current loop of 41.5 *A*. This test is used to prove the proposed fault detection system under a more severe load fluctuation condition. Fig. 6 gives the negative sequence current while the motor is operated under healthy and fault condition in presence of load fluctuation from 6.5 to 15 *sec*. It can be observed that the value of negative sequence current has a more noticeable deviation from the ones of no load condition. Fig. 7 shows the output of the purposed FDD. Clearly, the effect of the load fluctuation in this indicator is significantly reduced.

Results in both case studies demonstrate that the proposed method is capable of detecting incipient faults even in severe load transients. Additionally, the indicator shows a strong correlation between its magnitude and the level of severity. This is illustrated in Table II, from where it can be observed that the fault indicator, I_{a2}, almost decrease proportionally as the fault severity decreases. Hence the proposed fault indicator behaves in a predictable manner in evaluating the fault severity. This is a very important aspect for online condition monitoring in practical applications.

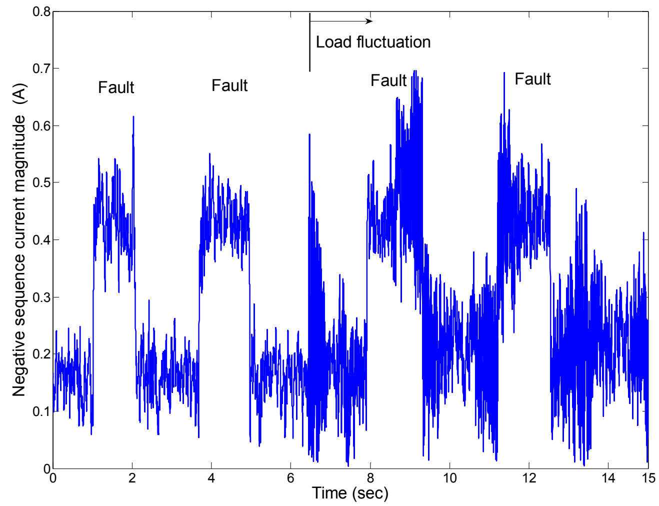

Fig. 4. Negative sequence current (Loop current 25 *A*. 0-30% load).

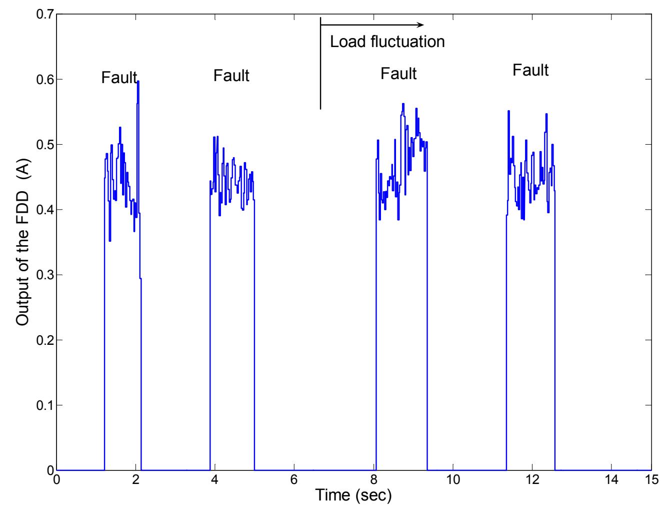

Fig. 5. Output of the FDD purposed (Loop current 25 *A*. 0-30% load)

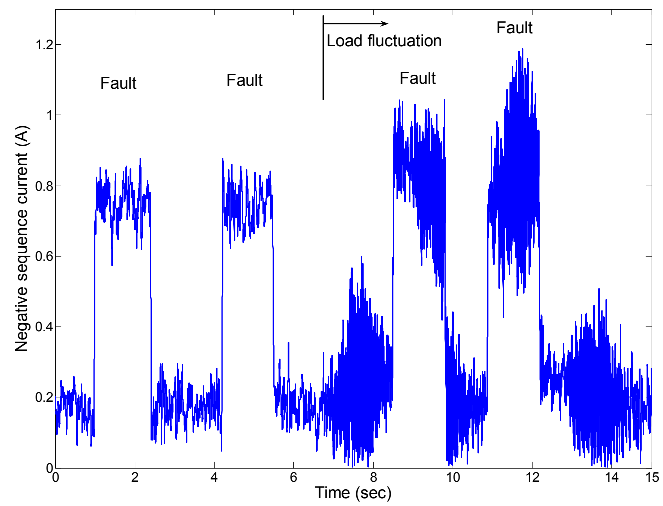

Fig. 6. Negative sequence current (Loop Current 41.5 *A*. 0-45% load)

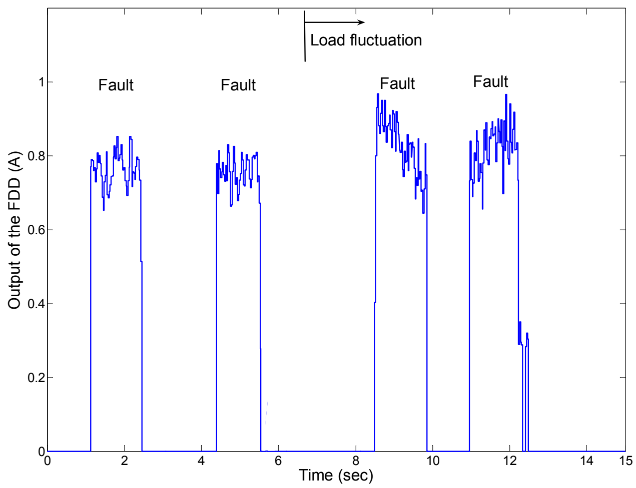

Fig. 7. . Output of the FDD purposed (Loop current 41.5 A. 0-45% load)

TABLE II. CORRELATION OF LOOP CURRENT, PERCENTAGE OF SHORTED WINDING IN PHASE A AND PORCENTAGE OF THE ADJUSTED NEGATIVE SEQUENCE CURRENT INCREASE

Implementation	Loop Current (*A*)	Shorted windings (*%*)	Increase in I_{a2} (*%*)
Taps	115	12.5%	2500
	75	6.25%	780
Variable Resistor	65	6.25 % + R1	700
	41	6.25 % + R2	415
	25	6.25 % + R3	250

Fig. 8 illustrates the benefit of using the fuzzy logic system over using either current or impedance negative sequence individually in the detection stage under load fluctuations. The three signals shown in this figure are the negative sequence impedance, the adjusted negative sequence current, and the output of the fuzzy logic based fault detection system, in corresponding to their threshold. In order to compare the three fault indicators accurately, the adjusted negative sequence current and the fault detection output are scaled by 20 times and 10 times, respectively. According to this figure the adjusted negative sequence current indicator is able to detect the fault occurring in the time interval of 5.3 - 7.2 *sec*, but it generates false alarms in the time interval between 2 and 3 *sec*, which is a healthy condition of the motor. On the other hand, the negative sequence impedance indicator performs properly under healthy conditions, but it misses the fault at some time instants. Effectiveness of the proposed fault detection is clearly observed from this comparison in discriminating the motor condition reliably and consistently under load fluctuations.

V. CONCLUSION

In this paper, a novel fault detection method is proposed using fuzzy logic in combination with negative sequence analysis for the detection of PMSM stator winding short circuit fault. Application of fuzzy logic during the fault detection stage enhances the FDD robustness against external disturbances, such as load fluctuations. Experimental study shows that the proposed detection approach is not only immune to load fluctuation, and other inherent asymmetries of the motor, but also capable of providing a measurement of the severity level of the stator interturn short fault. For all the tests carried out, the fault is identified promptly and properly. In the future, this work will be extended to consider the asymmetries caused by unbalance voltage supplies.

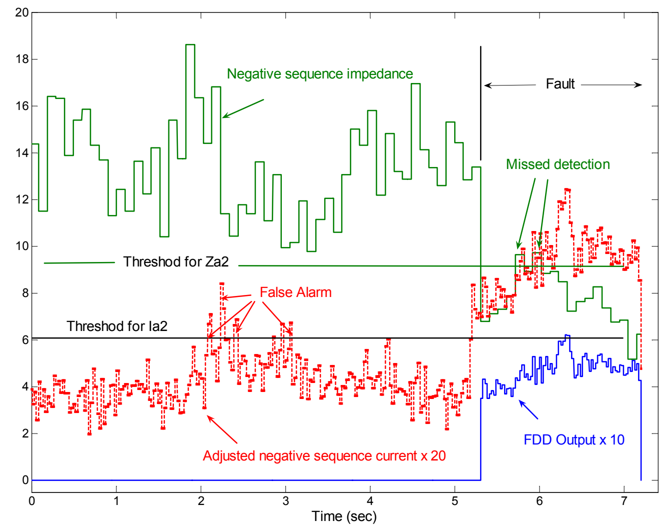

Fig. 8. Proposed FDD method versus negative sequence current/impedance

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