DETECTION OF INCIPIENT FAILURES USING AN H_2-NORM CRITERION: APPLICATION TO ELECTRIC POINT MACHINES

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Abstract: The paper deals with condition monitoring of electric switch machines for railway points. The proposed detection system is based on off-line processing of armature current and voltage sampled as the machine operates a switch of railway tracks. The system, consisting of an algorithm tuned on a model of the machine as both the rails are driven towards their rest positions, allows detection of faults of an incremental nature, i.e. those connected to progressive increase of frictional loads (loss of lubrication, deterioration of slide chairs, increasing obstructions, etc). The algorithm realizes a finite impulse response system whose convolution profiles are designed on the basis of an H_2-norm criterion which guarantees robustness, particularly with respect to electrical noise.

Keywords: Power plants and power systems, Fault detection, Railway points

1. INTRODUCTION

Economic and environmental reasons have recently forced railway infrastructure administrations to invest more in research and development items, in order to optimize their supply. This process has evolved in two directions. The first is the production of new generations of trains and railway systems based on new technologies (Mirabadi *et al.*, 1996). The other direction is improvement of the existing infrastructures in order to reduce maintenance costs and provide higher levels of reliability and safety. In this context, special attention is paid to railway signalling equipment, which failure statistics have shown to be responsible for a remarkably high number of service disruptions and delays (Railtrack, 2001). In particular, studies focused on conventional railway signalling failures have shown that the reliability of railway points is crucial to service efficiency (IRSE, 1994), (SASIB, 1994). The use of well-proven components combined with frequent site visits and planned maintenance has enabled a good standard of quality to be achieved. However, service disruptions and safety concerns related to on-site inspections, rising costs of qualified workforce and progressively decreasing costs of microelectronics and information technologies have induced railway infrastructure management to evaluate implementation of large-scale computer-based condition monitoring. Thus, a great deal of research effort has recently been directed towards condition monitoring and fault detection for railway point machines (Roberts *et al.*, 2002), (Zhou *et al.*, 2002), (Oyebande and Renfrew, 2002). Although each of these works proposes an original solution, they all share the same off-line option, which neatly distinguishes their approach from those more often encountered in the fault detection and isolation literature. In fact, most fault diagnosis systems operate on wide industrial plants or complex processes and systems (e.g. nuclear power plants, chemical and petrochemical processes, aerospace control systems). Since in those applications safety and quickness of intervention

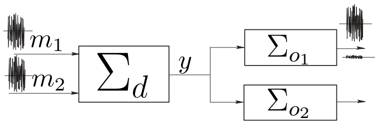

Fig. 1. H_2-norm approach to fault detection

are a must, fault diagnosis is carried out by highly sophisticated real-time systems. In conventional railway point machines, a simple emergency device causes immediate and safe service disruption in case of failure. Thus, a low-cost off-line condition monitoring system whose objective is detecting anomalies which would turn into failures in the long term appears to be the most appropriate solution. Also the detection system proposed in this paper is off-line. However, it totally differs in the methodology adopted to design the detection unit, whose job is to detect faults of an incremental nature by using recorded sequences of armature current and voltage in the presence of electrical noise. This methodology arises from the geometric approach to fault detection and noninteraction (Basile and Marro, 1970), (Massoumnia, 1986), (Massoumnia *et al.*, 1989), (Basile and Marro, 1992). However, since exact conditions for structural fault detection are not satisfied by the system under consideration, an H_2-norm optimization technique is adopted. According to (Frank and Wünnenberg, 1989), the performance index is defined as the ratio of the L_2-norm of the outputs of the observer unit due to the fault input and the noise, respectively. Thus, the residual is optimal in the sense that the effects of the fault are maximal with respect to the effects of the disturbance. Several features distinguish the present approach from that of (Frank and Wünnenberg, 1989). First, the design of the observer unit is carried out in the dual setting of noninteraction: as the investigation of exact conditions was first performed in the control field, it seems convenient to follow the same path in the investigation of optimization techniques. Moreover, the design of the noninteracting control units is based on an H_2-norm approach which also takes into account the main constraints introduced by practical implementation requirements: i) finite control horizon; ii) finite control energy; iii) zero final state. Finally, the algorithmic implementation of these units is achieved through finite impulse response systems.

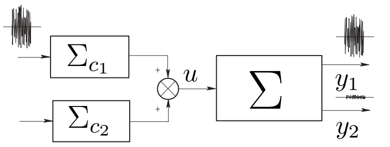

Fig. 2. H_2-norm approach to noninteraction

2. BASICS OF CONSTRAINED H_2-NORM FAULT DETECTION AND NONINTERACTION

Consider the fundamental FD problem, where the fault inputs are partitioned into two blocks (Fig. 1). In the H_2-norm approach, the observer unit Σ_{o_1} should be such that the H_2-norm of the transfer function matrix from the first fault to the first residual over the H_2-norm of the t.f.m. from the second fault to the same first residual is maximal. The observer unit Σ_{o_2} should be designed likewise. If the faults are partitioned into more than two blocks, the design of the observer units should be carried out by still considering a two-block partition: the first block is the fault input associated to the observer unit to be designed, the second collects all the other faults. Disturbances are also grouped in this latter block. In the NI context, the criterion is expressed as follows. Again, consider the fundamental problem, where the controlled outputs are partitioned into two blocks (Fig. 2). Assume that Σ is internally stable. In the design of Σ_{c_1}, the target is maximizing the ratio of the H_2-norm of the t.f.m. from the first input to the first controlled output over the H_2-norm of the t.f.m. from the same first input to the second controlled output. A similar criterion holds for devising Σ_{c_2}. Again, if the controlled outputs are partitioned into more than two blocks, each compensation unit should be designed by considering the corresponding output with respect to the set of all the others. The H_2-norm FD and NI problems are then considered in a modified form including the major constraints imposed by practical implementation mentioned in the Introduction. To ensure that the problem is well-posed, the system is assumed to be reachable and the final time of the control interval is assumed to be greater or equal to the controllability index. Thus, the design of each precompensation unit requires the solution of a problem stated as Problem 1, which specifically focuses on the design of Σ_{c_1}.

Problem 1. (H_2-noninteraction with constraints). Refer to Fig. 2. Let Σ be ruled by

$$x(t+1) = A\,x(t) + B\,u(t), \tag{1}$$

$$y_1(t) = C_1\,x(t) + D_1\,u(t), \tag{2}$$

$$y_2(t) = C_2\,x(t) + D_2\,u(t), \tag{3}$$

with state $x \in \mathbb{R}^n$, control input $u \in \mathbb{R}^p$, controlled outputs $y_1 \in \mathbb{R}^{q_1}$ and $y_2 \in \mathbb{R}^{q_2}$. Let (A, B) be reachable. Let $x(0) = 0$. Let $N \in \mathbb{Z}^+$ satisfy $N \geq \nu$, where $\nu \in \mathbb{Z}^+$ denotes the controllability index of (A, B). Find a control sequence $u(t)$, $0 \leq t \leq N$, such that the performance index $J = \sum_{t=0}^{N} y_1(t)^\top y_1(t) \,/\, \sum_{t=0}^{N} y_2(t)^\top y_2(t)$ is maximal under the constraints $\sum_{t=0}^{N} u(t)^\top u(t) = 1$, and $x(N) = 0$.

Problem 2. (Mathematical programming problem with constraints). Consider (1), (2), (3). Let (A, B) be reachable. Let $N \geq \nu$, with $N, \nu \in \mathbb{Z}^+$ and ν the controllability index of (A, B). Let

$$u_N = \left[\, u(0)^\top \;\; u(1)^\top \;\ldots\; u(N)^\top \,\right]^\top, \tag{4}$$

$$y_{Ni} = \left[\, y_i(0)^\top \;\; y_i(1)^\top \;\ldots\; y_i(N)^\top \,\right]^\top, \qquad i = 1, 2,$$

$$B_{Ni} = \begin{bmatrix} D_i & O & \cdots & O \\ C_i B & D_i & \cdots & O \\ \vdots & \vdots & \ddots & \vdots \\ C_i A^{N-1} B & C_i A^{N-2} B & \cdots & D_i \end{bmatrix}, \; i = 1, 2,$$

$$L_N = \left[\, A^{N-1} B \;\; A^{N-2} B \;\cdots\; B \;\; O \,\right].$$

Find a vector u_N such that the performance index $J = \|B_{N1}\, u_N\|_2^2 / \|B_{N2}\, u_N\|_2^2$ is maximal under the constraints $\|u_N\|_2 = 1$ and $L_N\, u_N = 0$.

Theorem 1. Problems 1 and 2 are equivalent. (Marro and Zattoni, 2004)

Theorem 2. Refer to Problem 2. Let K_N be a basis matrix of $\ker L_N$. Let $M_i = K_N^\top B_{Ni}^\top B_{Ni} K_N$, with $i = 1, 2$. Let λ^o be the greatest generalized eigenvalue of the pencil $\lambda M_2 - M_1$ and let t^o be the corresponding eigenvector. Then, $u_N^o = K_N\, t^o / \|K_N\, t^o\|_2$ solves Problem 2. (Marro and Zattoni, 2004)

Once u_N^o has been evaluated according to Theorem 2, $u^o(t)$, $0 \leq t \leq N$, is retrieved by virtue of Theorem 1. The control sequence $u^o(t)$, $0 \leq t \leq N$, can be produced by applying a unit sample (i.e. a sequence $\delta(t)$, with $t = 0, 1, \ldots$, s.t. $\delta(0) = 1$ and $\delta(t) = 0$ for all $t \neq 0$) to a discrete-time finite impulse response system whose IO equation is

$$u_1(t) = \sum_{\ell=0}^{N} \Phi_{c_1}(\ell)\, h_1(t - \ell), \qquad t = 0, 1, \ldots, \tag{5}$$

$$\Phi_{c_1}(\ell) = u^o(\ell), \qquad \ell = 0, \ldots, N. \tag{6}$$

Thus, Σ_{c_1} in Fig. 2 is described by (5),(6) or, equivalently, by $(A_{c_1}, B_{c_1}, C_{c_1}, D_{c_1})$ with

$$A_{c_1} = \begin{bmatrix} 0 & 1 & 0 & \ldots & 0 \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & 0 \\ \vdots & \ddots & \ddots & \ddots & 1 \\ 0 & \ldots & \ldots & \ldots & 0 \end{bmatrix}, \quad B_{c_1} = \begin{bmatrix} 0 \\ \vdots \\ \vdots \\ \vdots \\ 0 \\ 1 \end{bmatrix}, \tag{7}$$

$$C_{c_1} = \left[\, \Phi_{c_1}(N) \;\ldots\; \Phi_{c_1}(1) \,\right], \quad D_{c_1} = \Phi_{c_1}(0). \tag{8}$$

The unit Σ_{c_2} should be devised likewise, with the outputs $y_1(t)$ and $y_2(t)$ playing reverse roles in the performance index. Denoting by $u_1(t)$ and $u_2(t)$ the outputs of Σ_{c_1} and Σ_{c_2}, the control input $u(t)$ applied to Σ is $u(t) = u_1(t) + u_2(t)$.

The solution of the corresponding FD problem is obtained through duality arguments. Refer to Fig. 1. The FD problem is stated for the system Σ_d ruled by

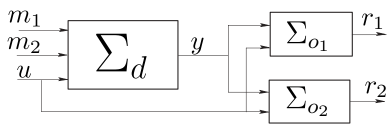

Fig. 3. Compensation of measurable inputs in FD

$$x(t+1) = A\, x(t) + L_1\, m_1(t) + L_2\, m_2(t), \tag{9}$$

$$y(t) = C\, x(t) + N_1\, m_1(t) + N_2\, m_2(t), \tag{10}$$

with state $x \in \mathbb{R}^n$, fault inputs $m_1 \in \mathbb{R}^{q_1}$ and $m_2 \in \mathbb{R}^{q_2}$, measurable output $y \in \mathbb{R}^p$. Let the matrices A, L_1, L_2, C, N_1, N_2 in (9),(10) be the transpose of A, C_1, C_2, B, D_1, D_2 in (1),(2),(3), respectively. Then, the observation units Σ_{o_1} and Σ_{o_2}, respectively described by the quadruples $(A_{o_1}, B_{o_1}, C_{o_1}, D_{o_1})$ and $(A_{o_2}, B_{o_2}, C_{o_2}, D_{o_2})$, can be directly derived from Σ_{c_1} and Σ_{c_2} with the correspondences $A_{o_1} = A_{c_1}^\top$, $B_{o_1} = C_{c_1}^\top$, $C_{o_1} = B_{c_1}^\top$, $D_{o_1} = D_{c_1}^\top$, and $A_{o_2} = A_{c_2}^\top$, $B_{o_2} = C_{c_2}^\top$, $C_{o_2} = B_{c_2}^\top$, $D_{o_2} = D_{c_2}^\top$.

3. COMPENSATION OF MEASURABLE SIGNALS IN FAULT DETECTION AND NONINTERACTION BY FIR SYSTEMS

In order to guarantee insensitivity of the residuals to command signals applied to the monitored system, also these latter should be processed by the residual generators. Hence, additional units to be included in the residual generators should be devised. To this aim, we will proceed by duality arguments. First, refer to Fig. 3 and let Σ_d be ruled by

$$x(t+1) = A\, x(t) + L\, m(t) + B\, u(t), \tag{11}$$

$$y(t) = C\, x(t) + N\, m(t) + D\, u(t), \tag{12}$$

where $m = [\, m_1^\top \;\; m_2^\top \,]^\top \in \mathbb{R}^q$ and $u \in \mathbb{R}^s$ are the manipulable and fault inputs, respectively. Then, refer to Fig. 4. The noninteraction problem is stated for the new system Σ, ruled by

$$x(t+1) = A\, x(t) + B\, u(t), \tag{13}$$

$$y(t) = C\, x(t) + D\, u(t), \tag{14}$$

$$e(t) = E\, x(t) + F\, u(t), \tag{15}$$

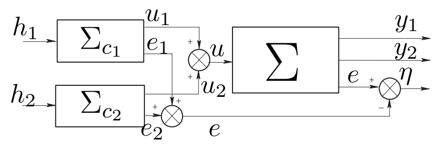

Fig. 4. Compensation of measurable outputs in NI

where $y = [\, y_1^\top \;\; y_2^\top \,]^\top \in \mathbb{R}^q$ and $e \in \mathbb{R}^s$ are the controlled and measurable outputs, respectively, and where the matrices A, B, C, D, E, F are the transpose of A, C, L, N, B, D in (11),(12), respectively. In this context, the problem is to design the additional units to be included in the precompensators so that the new output $\eta(t)$ is insensitive to the inputs $h_1(t)$ and $h_2(t)$. Let us focus on the design of the additional unit to be included in Σ_{c_1}. According to (5), (6), the impulse response of Σ_{c_1} is the sequence $u_1(t) = \Phi_{c_1}(t)$, with $t = 0, \ldots, N$, and $u_1(t) = 0$, with $t > N$. The state and output trajectories of Σ, due to the forcing action $u(t) = u_1(t)$, $t \geq 0$, are completely determined. In particular, let us denote by $\bar{e}_1(t)$, $t \geq 0$, the trajectory of the output $e(t)$ corresponding to the application of $u(t) = u_1(t)$, $t \geq 0$. Since $u_1(t) = 0$ with $t > N$ and $x(N) = 0$, $\bar{e}_1(t) = 0$ with $t > N$. Let $\bar{e}_{1_N} = [\, \bar{e}_1(0)^\top \;\; \bar{e}_1(1)^\top \;\; \ldots \;\; \bar{e}_1(N)^\top \,]^\top$. Then, $\bar{e}_1(t)$ with $t = 0, \ldots, N$, can be retrieved from $\bar{e}_{1_N} = B_N \, u_N$, where u_N is defined as in (4) and

$$B_N = \begin{bmatrix} F & O & \cdots & O \\ EB & F & \cdots & O \\ \vdots & \vdots & \ddots & \vdots \\ EA^{N-1}B & EA^{N-2}B & \cdots & F \end{bmatrix}.$$

The sequence $\bar{e}_1(t)$, $t = 0, \ldots, N$, can be produced as the impulse response of the FIR system

$$e_1(t) = \sum_{\ell=0}^{N} \Psi_{c_1}(\ell)\, h_1(t-\ell), \quad t = 0, 1, \ldots, \qquad (16)$$

$$\Psi_{c_1}(\ell) = \bar{e}_1(\ell), \quad \ell = 0, \ldots, N. \qquad (17)$$

A description equivalent to (16),(17) is the quadruple $(A_{c_1}, B_{c_1}, E_{c_1}, F_{c_1})$, where A_{c_1} and B_{c_1} are defined as in (7) and

$$E_{c_1} = \left[\, \Psi_{c_1}(N) \;\ldots\; \Psi_{c_1}(1) \,\right], \qquad F_{c_1} = \Psi_{c_1}(0).$$

By including the FIR system (16),(17) in the precompensation unit Σ_{c_1} and another FIR system, designed according to similar criteria, in Σ_{c_2}, compensation of the measurable output $e(t)$ is achieved, according to the scheme shown in Fig. 4. Then, the additional units to be included in Σ_{o_1} and Σ_{o_2} are simply obtained by transposition of Σ_{c_1} and Σ_{c_2}, respectively.

4. THE TYPE P80 ELECTRIC SWITCH MACHINE

The type P80 electric switch machine is a motor-driven device conceived to operate switches of railway points (Fig. 5). It is equipped with a 0.39 kW permanent magnet motor nominally 120 Vdc, weathertight connectors for power supply, a clutch which slips at a predetermined load setting to prevent damage to the motor if points are obstructed, and a lock detection circuit which indicates the switch rail and locks bar positions.

Fig. 5. Type P80 electric switch machine

Figure 6 shows a schematic diagram of a point machine installation. On application of voltage, the blades switch between two rest positions, usually designated as ‘normal’ and ‘reverse’. In the normal position, the inner switchblade (that closer to the point machine) lies against its stockrail, while the outer one is far from the corresponding stockrail. In both cases, the points are locked and the lock detection circuit is completed. Two different routes can be set up depending on the position selected. The following steps are involved in the operation of the point machine from the normal to the reverse rest position, ‘normal operation’. The point machine is activated by application of voltage. First, the outer blade is unlocked and driven towards the stockrail. Afterwards, the inner switchblade is also unlocked and driven away from the stockrail. Then, both the blades are simultaneously pulled towards their new rest positions. Towards the end of the stroke, an increased force is encountered as the outer switchblade is bent elastically against the stockrail and locked. Finally, the inner switchblade also reaches the new rest position and is locked. The motor runs down, the detection contacts confirm the position and the new route is set safely. The reverse operation develops in a similar way, with the roles played by the inner and outer blades reversed. For more details on constructive and operational features of the type P80 switch machine, the reader should refer to (Luzzi *et al.*, 1998), (ALSTOM, 1999).

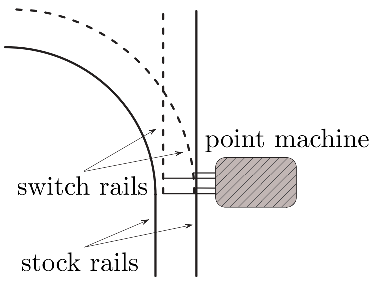

Fig. 6. Point machine installation

Table 1. Point machine parameters

Parameter	Symbol	Numerical Value
Armature resistance	R_a	$11\,\Omega$
Armature inductance	L_a	$4.2 \cdot 10^{-3}$ H
Speed constant	K_e	$220 \cdot 10^{-3}$ Vs/rad
Torque constant	K_t	$220 \cdot 10^{-3}$ Nm/A
Motor inertia	J	10^{-3} Kg m^2
Motor damping	B	$0.6325 \cdot 10^{-3}$ Nms/rad
Stiffness constant	K_l	$0.25 \cdot 10^{-3}$ Nm/rad

The fault detection system will be based on a mathematical model describing the behaviour of the point machine when both the blades are far from the stockrails and simultaneously driven towards the respective rest positions. Experimental results have shown that in this phase of the manoeuvre the point machine approximately behaves according to the LTI model

$$L_a \frac{di_a(t)}{dt} = -R_a\, i_a(t) - K_e\, \omega(t) + v_a(t), \quad (18)$$

$$J \frac{d\omega(t)}{dt} = K_t\, i_a(t) - B\, \omega(t) - c_r(t), \quad (19)$$

where $v_a(t)$, $i_a(t)$, $\omega(t)$ and $c_r(t)$ respectively are armature voltage, armature current, angular velocity and torque load, and where R_a, L_a, K_e, J, K_t and B respectively are armature resistance, armature inductance, speed constant, motor-load inertia, torque constant and motor damping. Electrical noise on the armature voltage is taken into account by an additive term $\Delta\, v_a(t)$ in (18). The armature current is the measurable output. In optimal operating conditions, the torque load is approximately a linear function of the angular position of the blades (hence, of the rotor). However, in the presence of obstructions, an additive term perturbs the linear dependence, i.e.

$$c_r(t) = K_l\, \vartheta(t) + a(t), \quad (20)$$

where $\vartheta(t)$ and $a(t)$ are rotor angular position and frictional load, while K_l is the switch-rail stiffness. Let $x(t) = [\, i_a(t) \;\; \omega(t) \;\; \vartheta(t)\,]^\top$, $u(t) = v_a(t)$, $m(t) = [\, a(t) \;\; \Delta v_a(t)\,]^\top$ and $y(t) = i_a(t)$. Hence, a state-space model

$$\dot{x}(t) = A\, x(t) + L\, m(t) + B\, u(t), \quad (21)$$

$$y(t) = C\, x(t), \quad (22)$$

with appropriate matrices A, L, B and C, can be easily derived from (18),(19),(20). The numerical values of the point machine parameters are subject to variations. Since validation of the proposed method will be carried out on the basis of data sequences logged through experimental tests performed by Alstom at Milan Fiorenza IDP multipurpose facility (Ciampolini and Pinasco, 1999), we will consider the values of the parameters in that experimental set up (Table 1).

5. RESIDUAL GENERATOR DESIGN AND EXPERIMENTAL RESULTS

Since the point machine is equipped with a detection circuit providing information on whether the operation was safely completed or not, the detection system is focused on recognizing anomalous frictional loads by processing sequences of armature current and voltage recorded in operations which successfully ended despite anomalies. The sequences to be processed are those normally logged by FS (Italian Railways) with sampling time 0.05 s. Thus, a sampled-data model equivalent to (21),(22) with the numerical values of Table 1 is derived by ZHO-sampling with $T_s = 0.05$ s. The length of the FIR system window has been selected of 20 samples on the basis of the length of the detection window and its allocation within the whole manoeuvre. In fact, the detection system is based on the linear model of the point machine, which holds only within a particular phase of the machine operation also called 'detection window'. It corresponds to the time interval between about 1.25 s and 2 s in a normal or reverse operation lasting about 2.9 s. In order to obtain effectiveness of the FIR system filtering action, the FIR system window should be at least equal to the detection window. On the other hand, in order to avoid degradation of results due to the strong nonlinearities in the initial transient, the FIR system window should not exceed $20 \div 25$ samples. Hence, the residual generator Σ_{o_1} devised according to the procedures shown in Sections 2 and 3 detects the presence of the anomalous term $a(t)$ with 'sufficiently' low sensitivity to armature voltage uncertainties $\Delta v_a(t)$. In fact, $J^o = 1.3899 \cdot 10^3$. In Fig. 7 the gain Φ_{c_1} of the FIR system for residual generation and the gain Ψ_{c_1} of that for the compensation of the manipulable input are plotted as functions of ℓ. The detection unit devised has been tested through application of unit samples and white noise to the system inputs a and $\Delta\, v_a$. The ratio of the root mean squares of the residuals evaluated on 1000 samples was found to be $1.3821 \cdot 10^3$ and $1.2189 \cdot 10^3$, respectively.

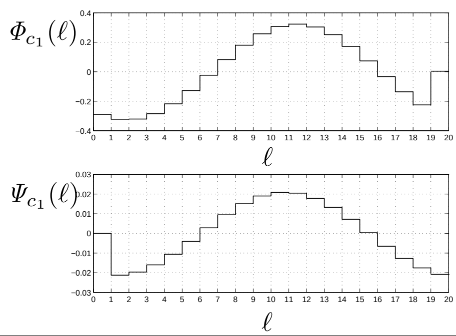

Fig. 7. Gains of the FIR system

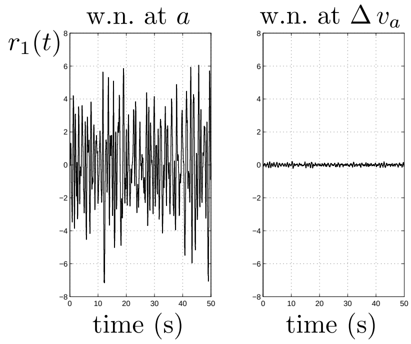

Fig. 8. Residual r_1 with unit samples at a (left) and Δv_a (right)

Finally, the detection unit has been tested on recorded sequences of the armature current and voltage logged in the Milan Fiorenza IDP experimental set up. In those tests, the presence of anomalous frictional loads was simulated by progressive silt up of the point machine ball bearings. Values of the residual root mean squares in different operating conditions are shown in Table 2. The computation has been restricted to the detection window. Normal and reverse manoeuvres produce different r.m.s. values, due to constructive asymmetries of the P80 switch machine. In optimal conditions, r.m.s. are nonetheless different from zero: this is due to unavoidable model uncertainties. However, anomalous frictional loads can be detected by comparing the residual r.m.s. for a given recorded sequence with that obtained in nominal conditions. Superposition of electrical noise with unit intensity would not substantially modify the final decision due to the sufficiently high value of the performance index obtained with the FIR system window of 20 samples.

6. CONCLUSIONS

The proposed method to monitor the operating conditions of electric switch machines yields a residual generator processing selected data directly available from railway conventional infrastructures and does not require additional instrumentation. The residual generator gain matrix is designed on an H_2-norm criterion which guarantees robustness with respect to disturbances. The proposed method is suitable for extension to any system which, in some step of its operation, admits a LTI model: many low-cost motor-driven devices (lifts, tool-machines, automatic doors and barriers) satisfy this requirement.

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Table 2. Residual rms (Milan Fiorenza IDP experimental set up)

experiment	*normal*	*reverse*
optimal condition	0.1492	0.1689
2 bearings silted	0.2054 (+38%)	0.2472 (+46%)
4 bearings silted	0.2316 (+55%)	0.2848 (+69%)
6 bearings silted	0.2477 (+66%)	0.3078 (+82%)

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