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FORCED DYNAMIC POSITION CONTROL OF PMSM WITH DTC UTILIZATION

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Almost one and a half century after the publication of Maxwell's On Governors, feedback theory with PID controllers in cascade structure is still an essential part of control structures of most controlled electric drives. There are a few control strategies which are "ready" to replace it but they usually miss one of the essential fundamentals of every successful approach — simplicity hand in hand with lucidity. But there is one close relative which is simple and powerful at the same time, is not excessively abstract and without complicated mathematics. The name of this technique is Forced Dynamic Control. In this paper forced dynamic control is presented together with direct torque controlled PMSM drive as unique combination of simple algorithms for inner and outer loop of cascade structure.

K e y w o r d s: forced dynamic control, DTC, position control, cascade structure

1 INTRODUCTION

There is one legitimate question: is it necessary to replace classical cascade feedback structures with an other structure even though in the majority of applications it is sufficient? The answer is positive when the alternative brings the same or better properties and another added value. In case of Forced Dynamic Control (FDC) the added value is simplicity. There are also other interesting approaches such as prediction algorithms [1,2], sliding mode control [3,4], neural networks [5,6] or the well known state space theory [7,8] with added value in *eg* better control of nonlinear systems, but these are too complex or abstract to reach a dominant position. FDC was first introduced in the mid 90's as a promising control method developed for broad spectrum of applications from management of information flow in communication networks [9] to road traffic control [10] and years of research have confirmed perfect behavior in the field of electric drives as well. It is easy for implementation due to the simple tuning and quite robust when appropriate observer is used.

FDC can work together with classical field oriented (vector) control (VC) in an inner loop but these approaches are not "equal" partners in the cascade structure. Equal in respect of complexity, because there is a simple FDC algorithm and on other side quite complex VC with a pair of PI controllers, additional transformation block or decoupling circuit, i.e. plenty of adjustable parameters and machine parameters variations. In an effort to find an equally simple inner loop algorithm as FDC and with the same or better properties as VC Direct Torque Control (DTC) was chosen as the best solution.

The idea of DTC is simple idea and it was thoroughly verified in industry for fifteen years (with induction machine). The absence of PI controllers and classical PWM algorithm means an advantage in comparison with VC. Only amplitudes of hysteresis bands must be adjusted. The utilization of hysteresis comparators brings the most serious drawback of this method: torque ripples. This paper deals with the implementation of electric drive position control with cascade structure containing DTC algorithm in inner loop and FDC algorithm in middle velocity loop. Only position loop is based on standard proportional feedback controller. The second section of this paper presents all loop controllers and simple observer. The simulation and experimental results and comparisons are presented in section 3.

2 CONTROL LOOPS

2.1 A. Forced dynamic control

FDC was developed in the middle of the nineties and was designed in the field of electric drives for induction motor, permanent magnet synchronous motor as well as for reluctance synchronous motor [11]. FDC can be applied to linear as well as nonlinear multivariable systems by linearizing about operating point and used with a position sensor or without it (with the utilization of appropriate observers).

In this paper the FDC algorithm is situated in the middle (velocity) loop where it provides the the desired dynamic behavior. The behavior or dynamic response is chosen by the user and is formulated in the time domain by a differential equation (1) or in other words equation of angular acceleration ? for FDC in velocity loop. It means equation of angular acceleration ε for FDC in velocity loop. There are many modes of desired dynamics from constant acceleration through S — curve to linear "n"-order mode. In this paper the basic first order linear dynamics describe by a simple equation will be used

$$\varepsilon = \dot{\omega}_r = \frac{\omega_r - \omega_d}{T_\omega} \tag{1}$$

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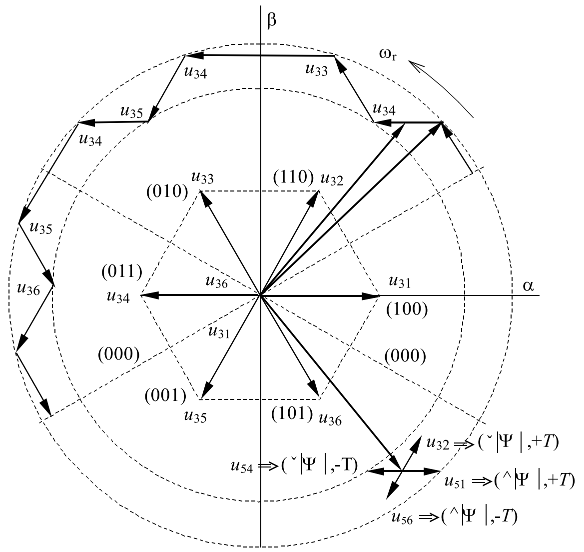

Fig. 1. Switching of voltage vector in the sector 2 and 6

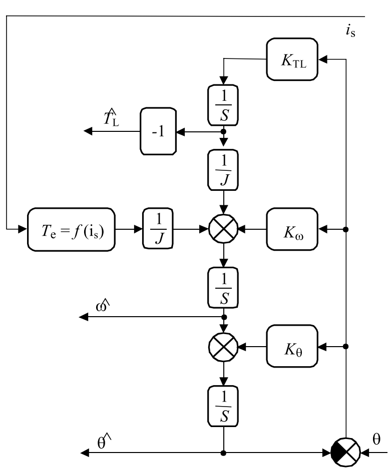

Fig. 2. Load torque observer

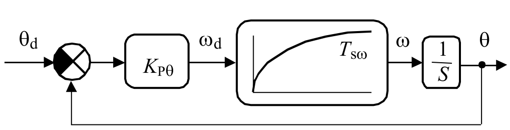

Fig. 3. Block diagram of position control structure with forced dynamic control algorithm

where ω_r and ω_d are real and demanded angular velocity and ε is angular acceleration. Time constant T_ω defines the desired bandwidth in frequency domain or settling time in time domain (according to [11]).

When we want to "force" system demanded dynamic behavior we need to know something about it *ie* to model it by a differential equation. Our system comprises permanent magnet synchronous motor (PMSM) and inverter which can be, due to simplification, neglected. The motor itself can be represented by the basic Newton's motion equation (for constant moment of inertia J and without friction)

$$\varepsilon = \dot{\omega} = \frac{T_e - T_L}{J} \tag{2}$$

where T_e, T_L is electromagnetic and load torque respectively and J is the moment of inertia.

The system will follow desired dynamics when the right hand side of equation (2) will correspond to the right hand side of equation (1). As it can be seen, FDC is closed relative with feedback linearization technique but it has a few advantages over it, such as compensation of disturbances.

2.2 Direct torque control

The basic principle of DTC [2] is very simple and is based on the selection of a proper stator voltage vector according to the differences between the reference and actual values of the stator flux and according to the electromagnetic torque demand.

The stator flux is forced to rotate by means of a suitable voltage vector and produces the desired torque. During this rotation, the magnitude of the stator flux is maintained in a defined hysteresis range as it is shown in Fig. 1. Here, in the second sector (θ_2), the third and fourth voltage vector will keep the vector of magnetic flux in a defined hysteresis range. The proper instantaneous voltage vector is chosen with regard to the output signals from hysteresis controller according to the switching table which can be described by equation (3).

$$\overline{u}_s = |s_T|\frac{2}{3}U_{DC}e^{j\left(\theta_{sc}+\frac{2\pi s_T}{3}=\frac{\pi s_T s_\Psi}{3}\right)} \tag{3}$$

where $\overline{u}_s$ is the stator voltage vector s_T and s_Ψ are outputs of hysteresis controllers, θ_{sc} is sector center angle and U_{DC} is DC bus voltage.

Described control technique brings a lot of advantages such as fast torque response, absence of PI controllers, absence of decoupling circuit and the most important overall simplicity of the method. The drawbacks of the method are torque and current distortion, variation of the switching frequency, high sampling frequency, selection of the same voltage vector to eliminate small and high torque (flux) differences *etc.* All these drawbacks can be minimized by using different modulation technique such as space vector modulation [13] but this is outside the scope of the paper.

2.3 The inner and the middle loop cooperation

As it can be seen from Fig. 4, the inputs of inner DTC loop are electromagnetic torque and magnetic flux modulus. To minimize losses, current or due to the power factor correction a proper optimization technique is chosen and according to it, stator magnetic flux modulus reference is defined [4]. The electromagnetic torque reference is taken from the output of the middle velocity loop. It is a result of interaction of equation (1) and (2) which form forced dynamic control law

$$T_{ed} = T_L + \frac{J}{T_\omega}(\omega_d - \omega_r)\,. \tag{4}$$

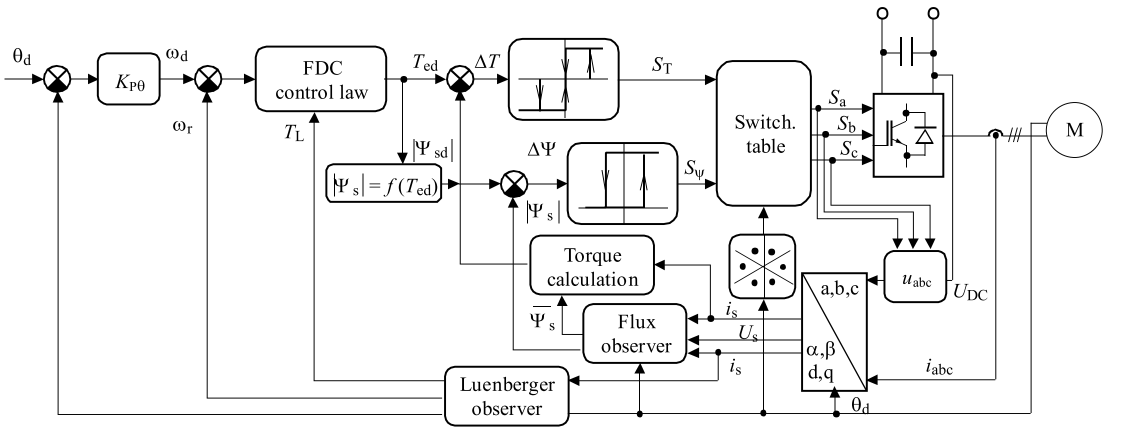

Fig. 4. Overall block diagram of the proposed control algorithm

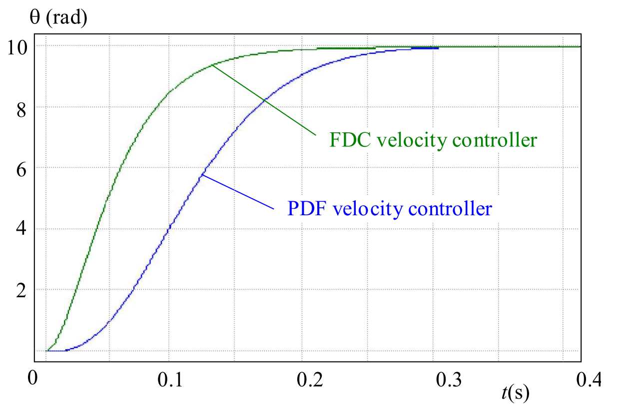

Fig. 5. Position controlled servodrive with PDF and FDC velocity controller with the same corner and characteristic frequency value with the step reference position responses (the simulation results)

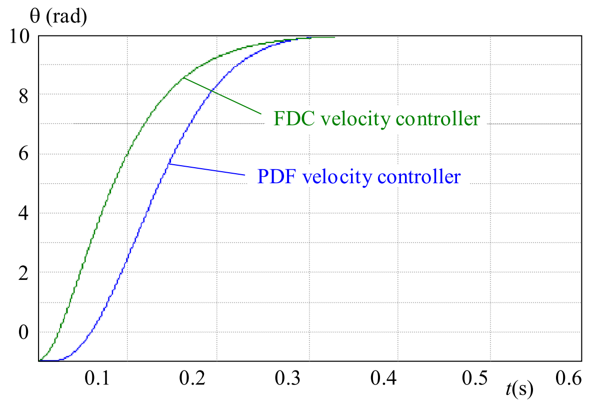

Fig. 6. Position controlled servodrive with PDF and FDC velocity controller with the same bandwidth ($16\,\mathrm{rad s}^{-1}$), with the step reference position responses (the simulation results)

The necessary condition is that load torque T_L must be known and the most effective way to obtain it is using an observer. For example Luenberger-based observer is more than suitable because, in addition, it provides the velocity signal without significant phase lag (which occurs after simple filtration) and therefore widen out system bandwidth. The load torque observer utilization dramatically improves dynamic response of the system. An example of observer can be seen in Fig. 2, where the observer core contains system model and simplest proportional correction gains that drive the error between real and estimated position to zero across a wide frequency range. The gains are set according to the desired bandwidth which must correspond to the loop bandwidth and with respect to sensor noise to provide correct results. A good method to obtain observer parameters is pole and zero placement [11]. The drawback of simple observer utilization is that it can cause problems when parameters variation occurs and more robust version should be used. Another approach, an additional sensor usage (for example torque or acceleration sensor based on the Ferraris principle), widens the bandwidth but increases the expenses.

2.4 Position control loop

With FDC algorithm in velocity loop, the outer position loop can be composed as a simple proportional controller in forward path. This simplest form of proposed algorithm (as a block diagram) is sketched in Fig. 3. To improve the system astatism, PI controller or another forward path can be added. The control structure parameters can be obtained by pole assignment method exploitation. Here the eigenvalues of the closed loop system matrix may be chosen to yield desired output behavior. With proportional controller in position loop, controller gain and time constant of middle loop are the only adjustable parameters but uniquely determined by forced desired dynamic characteristic as follows.

After choosing

$$G_{FDC}\left(s\right) = \frac{1}{1 + sT_{s\omega}} \tag{5}$$

the transfer function of structure in Fig. 3 is

$$G(s) = \frac{1}{s^2 + \frac{1}{T_{s\omega}}s + \frac{K_{P\theta}}{T_{s\omega}}} \tag{6}$$

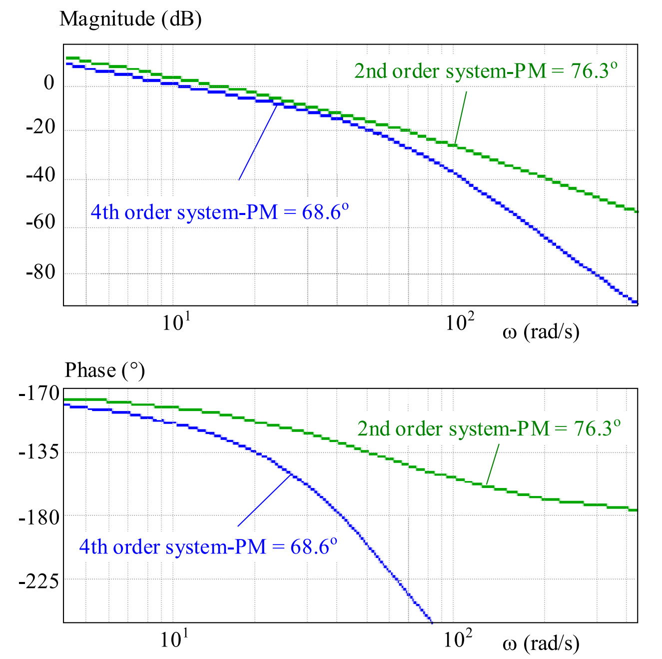

Fig. 7. Margins of stability — second and fourth order system bode diagrams from simulation (bandwidth 24 rads^{-1})

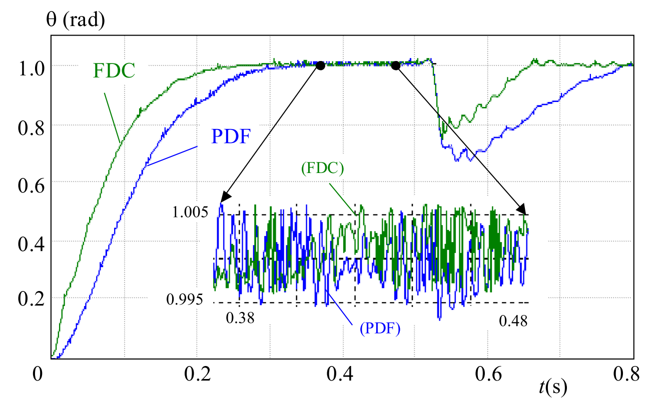

Fig. 8. Step position response of two servodrives — with PDF and FDC velocity controller — the experimental results

where $T_{s\omega}$ is settling time of angular velocity loop and $K_{P\theta}$ is position controller proportional gain. The desired dynamic behavior is represented by characteristic polynomial of the same order as (6)

$$s^2 + 2\xi\omega_0 s + \omega_0^2 = 0\,. \tag{7}$$

After the comparison of mentioned polynomials one can find out that only the bandwidth defined by characteristic angular frequency ω_0 and damping ratio ξ must be chosen. The bandwidth, related to cut-off frequency for second order system, is defined as follows

$$\omega_{cut\ \ off} = \omega_0 \sqrt{1 - 2\xi^2 + \sqrt{4\xi^4 - 4\xi^2 + 2}}\,. \tag{8}$$

Then the loop parameters are given as

$$K_{P\theta} = \frac{\omega_0}{2\xi}, \qquad T_{s\omega} = \frac{1}{2\xi\omega_0} \tag{9,10}$$

At the end of this section, overall block diagram of the proposed algorithm is presented in Fig. 4. It can be seen that the DTC algorithm is described in classical form with two hysteresis comparators. Proper design and adjustment are crucial for good functioning of the flux observer. A few realization possibilities are mentioned in [14].

The scheme in Fig. 4 has all the features of classical cascade structure but it does not contain PI controllers with number of adjustable parameters and unwanted delays or overshoots.

3 RESULTS AND COMPARISONS

The FDC position control and PDF position control will be both compared with DTC in the inner loop. Pseudo-derivative feedback (PDF) controller [15] was chosen due to its better dynamic properties (no zero in transfer function cancels overshoot). Incorporating the PDF controller results in the fourth order position system with a large phase lag in middle and high frequency region.

With FDC controller, the system (inner velocity loop) is forced to follow the first order dynamic behavior. Proportional position loop (with kinematic integrator) increases total system order by one grade. According to the simple control theory, the same value of corner frequency of PDF and characteristic frequency of FDC alternative gives shorter settling time for second one. It is obvious, because the bandwidth of second order system (with FDC controller) is higher. These circumstances are shown in Fig. 5, where position responses on step reference are shown, and where 35 rads^{-1} corner and characteristic frequency was chosen.

Similarly, when we chose the same bandwidth, the settling times will be similar but corner and characteristic frequency will be different and this means different curve shapes, as Fig. 6 with position responses on step reference shows.

Stability of both structures is defined by margins of stability (Fig.7) and as was indicated above the proposed structure gives significantly better results.

Figure 8 shows curves obtained from experiments with aforementioned position system structures that proved all mentioned advantages of position controlled control structure with DTC in inner and FDC algorithm in disturbance rejection ability but on the other hand increases middle loop.

The experimental stand consisted of surface mount PMSM coupled together with induction machine working as a load. The control algorithm has been exercised via multi-function data acquisition PC card.

The parameters of motor and control structure are listed in Table I.

Table 1. Motor, inverter and control structure parameters

Motor (DutymAx (DS) 75DSA)					
Speed n_n (min^{-1})	Voltage U_n (V)	Torque T_n (Nm)	Torque Const. K_T (Nm/A)	Inertia ($J\text{kg cm}^2$)	Current I_n (A)
3000	380	1.2	1.6	0.6	0.9
Inverter (VQFREM 400 004-4M)			Inner loop		
Power (kVA)	Current (A)	Effic. (–)	Switch. freq. (kHz)	Sampling ms	Hyst. band
6.9	10	0.975	2–8	0.1	0.05
Velocity loop		Position Loop		Observer	
Sampling (ms)	$T_{\Sigma i}$ (ms)	Sampling (ms)	Band-width (dB)	Sampling (ms)	Band-width (dB)
1	0.7	5	16	1	250

4 CONCLUSION

With minimum of mathematics and related computation power, alliance of forced dynamic control with direct torque control is more than equivalent alternative to classical control structures with PID controllers and VC utilization. The FDC provides perfect desired dynamic following and disturbance rejection qualities; on the other hand, DTC brings very fast inner loop operation to achieve unique dynamic characteristics. In the end, the user has only one task: to have an idea about the desired bandwidth and to set it. The velocity and position loops are set in a single step and thus algorithm provides very user friendly tuning.

This structure can be extended by a feedforward path to improve accuracy and repeatability of positional tasks. In delicate applications, where the weak point of this approach, the simple observer utilization, must be overcome, the implementation of more robust observer ([16], [17]), which provides more precise state variables extraction for the whole control structure (under wide conditions range) should take place.

The fact that Maxwell's findings [18] are still an essential part of the majority of industrial controllers proves their quality but an effort to improve them is more than essential. This paper brings one of the possibilities.

References

[1] DUCHAINE, V.—BOUCHARD, S.—GOSSELIN, C. M.: Computationally Efficient Predictive Robot Control, IEEE/ASME Trans. on Mechatronics **12** (Oct 2007), 570–578.

[2] CORTES, P.—KAZMIERKOWSKI, M. P.—KENNEL, R. M.—QUEVEDO, D. E.—RODRIGUEZ, J.: Predictive Control in Power Electronics and Drives, IEEE Trans. on Industrial Electronics, **55** No. 12 (Dec 2008), 4312–4324.

[3] BETIN, F.—SIVERT, A.—NAHID, B.—CAPOLINO, G. A.: Position Control of an Induction Machine using Variable Structure Control, IEEE/ASME Trans. on Mechatronics **11** (June 2006), 358–361.

[4] DAL, M.: Sensorless Sliding Mode Direct Torque Control (DTC) of Induction Motor, ISIE Proce. IEEE Inter. Symp. on Industr. Electronics,, vol. 3, June 2005, pp. 911–916.

[5] LIN, J-F.—FUNG, R-F.—WAI, R-J.: Comparison of Sliding-Mode and Fuzzy Neural Network Control for Motor-Toggle Servomechanism, IEEE/ASME Trans. on Mechatronics **3** (Dec 1998), 302–318.

[6] CONG, S.—LIANG, Y.: PID-Like Neural Network Nonlinear Adaptive Control for Uncertain Multivariable Motion Control Syst, IEEE Trans. on Industrial Electronics **56** No. 10 (Oct 2009), 3872–3879.

[7] BECK, H-P.—TURSCHNER, D.: Commissioning of a State-Controlled High-Powered Electrical Drive using Evolutionary Algorithms, IEEE/ASME Trans. on Mechatronics **6** (June 2001), 149–154.

[8] MIRANDA, H.—CORTES, P.—YUZ, J. I.—RODRIGUEZ, J.: Predictive Torque Control of Induction Machines Based on State-Space Models, IEEE Trans. on Industrial Electronics **56** No. 6 (June 2009), 1916–1924.

[9] DODDS, S. J.—GU, X.: Forced Dynamic Control, Proc. of the Conference on Advances in Information and Communication Engineering, AICE, Accra, Ghana, Aug 2005, pp. 3–8.

[10] DODDS, S. J.: Forced Dynamic Control: A Model Based Control Technique Illustrated by a Road Vehicle Control Application, Proceedings of the AC&T, School of Computing, Information Technology and Engineering, University of East London, UK, 2006.

[11] VITTEK, J.—DODDS, S. J.: Riadenie elektrických pohonov s vnútenou dynamikou (Forced Dynamics Control of Electric Drives), EDIS Žilina, 2003.

[12] TAKAHASHI, I.—NOGUCHI, T.: A New Quick Response and High Efficiency Control Strategy of Induction Motor, IEEE IAS Meeting, 1985, pp. 496–502.

[13] MALEK, M.—VITTEK, J.—VAVRÚŠ, V.—ŠTULRAJTER, M.: Application of Space Vector Modulation in Direct Torque Control of PMSM, AEEE/Elektro, University of Žilina, Slovakia.

[14] MALEK, M.: Servodrive Position Control of PMSM with Direct Torque and Flux Control, (in Slovak) dissertation thesis, ŽU Žilina, Slovakia, 2008.

[15] PHELAN, R. M.: Pseudo-Derivative Feedback (PDF) Control, UCRL-51036, University of California, Lawrence Livermore Laboratory, 1971.

[16] GAO, Z.—HU, S.—JIANG, F.: A Novel Motion Control Design Approach based on Active Disturbance Rejection, Proc. of the 40th IEEE Conference on Decision and Control, vol. 5, Orlando, FL, Dec 4–7 2001, pp. 4877–4882.

[17] MIKLOSOVIC, R.—RADKE, A.—GAO, Z.: Discrete Implementation and Generalization of the Extended State Observer, American Control Conference, Minneapolis, MN, June 14-16, 2006.

[18] MAXWELL, J. C.: On Governors, Proceedings of the Royal Society No. 100 (1868), 112.

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