Design of Separately Windings Control System of Series/Compound DC Traction Motors

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Abstract — **This paper focuses on the problem of the control system of Series/Compound DC motor in both areas of speed adjustment. Traditional field weakening is achieved by means of resistances and contactors wich inserting and/or shunting in field circuits. It is characterized by shock currents, torque and speed as well as by increased energy consumption. To eliminate these disavantages paper proposes separate control of armature, series and shunt windings of Series/Compound DC motor and supply their own power converters. Keeping hyperbolic mechanical characteristic of these motors requires setting the series field current equal to or less than armature current. Developed control system is equipped with a single loop for series field and two loops for armature with a current and speed controllers. Imposing series excitation current required is achieved through a special computer based on actual values of current and rotor speed. Control system design was made based on a mathematical model and use of default instrument of Matlab-Simulink for tuning of PID controllers. Simulation results demonstrate the system's ability to control separate windings for continuous speed adjustment in both areas, strictly limiting the rotor current, reducing energy consumption and ensuring the imposed performance indicators. The proposed control method is recommended for use in electric traction systems with Series/Compound DC Motors.**

I. Introduction

The paper refers to the adjustable traction system of trolleys with Series or Compound DC motors.

Thanks to the hyperbolic mechanical characteristics, the series or compound DC motor are used in large numbers in electric vehicles traction, including trams and trolleybuses [1]. The main problems for these kind of traction systems is the smooth adjustment of the speed and reducing the energy usage, things that can be solved using DC/DC power electronic converters [2].

Modern traction converters [3,4] ensure adjustment of the rotor circuit's voltage (armature and series field windings) of the Series DC motor, and of the shunt field winding's voltage in case of Compound DC motor. To weaken the series field flux, it is common to connect shunt resistances on the winding through contactors Fig.1, which leads to electromechanical shocks and a higher energy consumption. Command systems of these converters are structurally identical and contain 2 control loops in speed and current.

On method to eliminate the shunting shocks at field leak of the Compound DC motor consists in separate control of the armature, series and shunt field windings [5]. This paper represents an evolution of proposed method and it aim is to design of the separately control system of armature and field windings of Series/Compound DC motors. To demonstrate the correctness of the method is necessary to develop a mathematical model and computer simulation. Tuning of PID controllers is achieved by using the default tools of Matlab-Simulink.

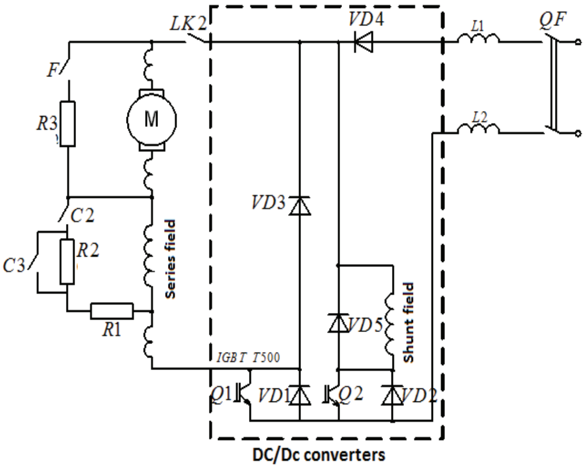

Fig.1. Traction system with Compound DC Motors and shunted of the series field

II. Traction system with separate excitation

The general structure of the Compound DC motor traction systeme with separate winidng control is presented in Fig.2. Each winding of the motor is supplyed separately through individual DC/DC converters, and the common functioning is ensured by a microprocessor control system.

To mantain the particularities, caused by series field, it is necessary that the control system to follow the instant value of the armature current and to impose the same current (for speed adjustment in the first zone) on the series field through its own DC/DC converter. To adjust the speed in the second zone by field weakining the series winding current will be lower than the armature current.

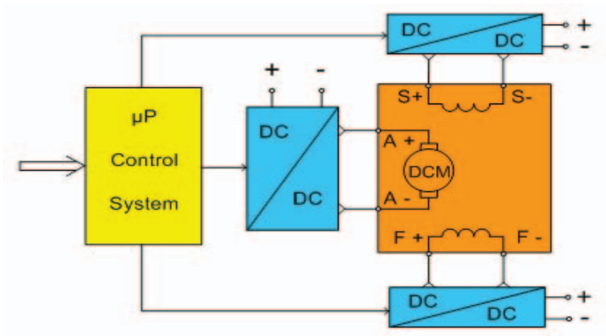

Fig.2. Traction system with Compound DC Motors and windings separate control

For the traction system of the trolleybus with Series DC motor with separate control of the windings, an automatic control system with a reaction loop of the current for the separate field series and in two loops, inner and outer, for the rotor circuit has been made Fig.3. The internal loop adjust the armature startup current *Ir*. Therefore, this control loop serves to limit the current. Current controller is responsible for limiting the start-up current, overloads and also contributes to the stability of the entire control system. Current limitation leads to lower brushes sparkling and rotor temperature, which ensures effective electronic protection and a substantial increase in terms of operation.

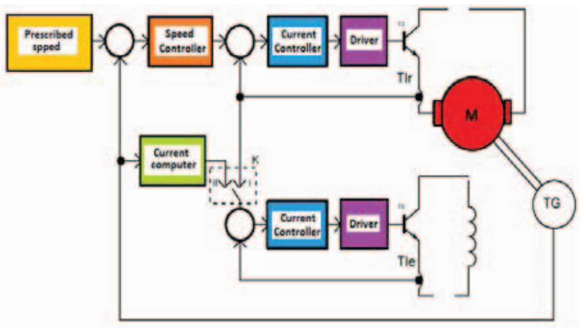

Fig.3. Control system of Series DC Motors with separately windings control

The outer loop is equipped with a speed controller which is the main regulator of the system, which is designed to maintain the speed constant at reference value n*. Excitation circuit contains a control loop that ensures the equality of currents $i_r = i_e$ for the first control zone and a subsequent decrease of i_e for flux weakening. In the systems examined above, adjustment in the second zone is achieved by shunting the winding, that is why adjustment is not smooth and is obtained in open loop.

This paper describes a method which allows to control, by the means of feedback loop, both zones. This method requires an algorithm by which the excitation current is inversely proportional to the speed decrease. Such a relationship is obtained from electromechanical equation of DC motor

$$\omega = \frac{U}{k \cdot \varphi} - I_r \frac{R_r}{k \cdot \varphi} \tag{1}$$

Since the magnetization curve of the magnetic circuit is

$$k\varphi = f(i_e) \tag{2}$$

From (1) and (2) we obtain (3), relationship used to control the second zone

$$i_e = f^{-1}\left(\frac{U - I_r R_r}{\omega}\right) \tag{3}$$

Virtual switch K, depending on the value of γ - duty cycle of the transistor, commutes the prescribed value from first to second control zone.

III. Mathematic model of Compound DC motor with separately windings control

According to the Compound DC motor's electric scheme with separate control Fig.4 the differential equations of the mathematical model are obtained (4):

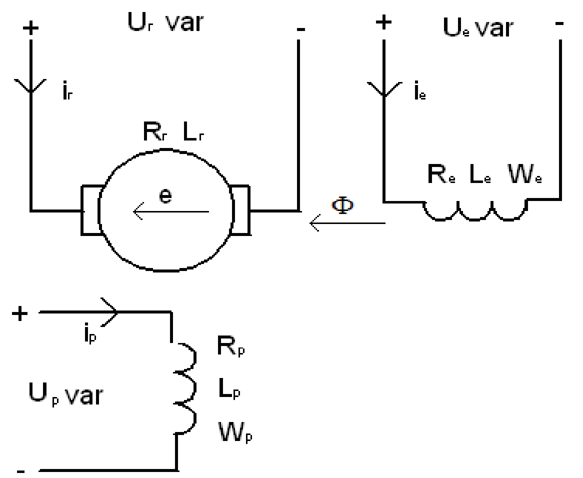

Fig.4. Scheme of Compound DC Motors with separately control

$$\left.\begin{aligned}
U_r &= i_r R_r + L_r \frac{di_r}{dt} + K\omega\Phi \\
U_p &= R_p i_p + 2p\sigma W_p \frac{d\Phi}{dt} \\
U_e &= R_e i_e + L_e \frac{di_e}{dt} + 2p\sigma W_e \frac{d\Phi}{dt} \\
\frac{J}{p}\frac{d\omega}{dt} &= K\Phi i_r - m_s \\
K\Phi &= f(i_p, i_e)
\end{aligned}\right\} \tag{4}$$

where R_r, L_r - armature resistance and inductance; R_e, L_e - resistance and inductance of series field; R_p, L_p - resistance and inductance of shunt field; W_e, W_p - number of turns of series and shunt windings; σ - leakage factor; Φ – magnetic field flux; ω – angular speed; $M = k\Phi i_r$ – electromagnetic torque; M_s – load torque; J – moment of inertia; $2p$ – number of pole pairs; $K\Phi = f(i_p, i_e)$ - the magnetization characteristics of Compound DC motor.

From (4) for Compound DC motor with separately windings control is obtained differential equations (5) under which the Simulink model was developed Fig.5.

$$\left.\begin{aligned}
&\frac{d\Phi}{dt}=\frac{1}{2p\sigma W_p}(U_p-R_pi_p)\\
&\frac{di_e}{dt}=\frac{1}{L_c}(R_ei_e+U_e\ -(U_p-R_pi_p)\frac{W_e}{W_p})\\
&\frac{di_r}{dt}=(U_r-R_ri_r-K\omega\Phi)\\
&\frac{d\omega}{dt}=\frac{p}{J}(K\Phi i_r-m_s)\\
&K\Phi=f(i_p,i_e),
\end{aligned}\right\}\qquad(5)$$

As it was mentioned above, the studied machine is a compound DC motor, therefore field flux simultaneously depends on two currents. In this paper is used only series winding while the parallel winding remains disconnected, so in parallel winding will not appear currents. Extrapolating the data we get a new characteristic $K\Phi=f(0,i_e)$. As result the Simulink model of Series DC motor is developed. Fig 5.

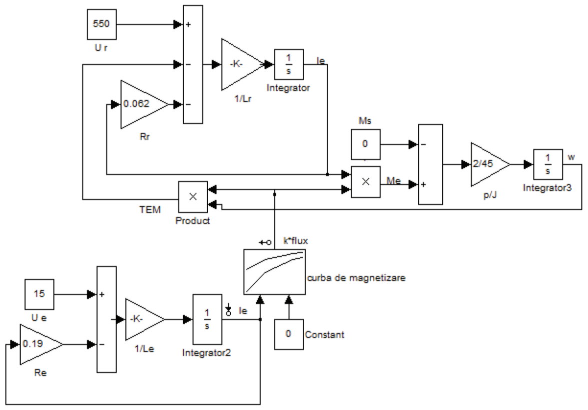

Fig 5. Simulink model of Series MCC with separately field control

IV. Simulink Model of Sparately Windings Control Systems of the Series DC Traction Motor

The Simulink model of the control system of the trolleybus with Series DC motor and separately field control is presented in Fig.6. The model contains subsystems of the trolleybus, drive motor, choppers and controllers in correspondence with the physical model Fig.3.

The system is provided with separate choppers for the armature and series windings, two PID regulators and current limitation devices for the rotor circuit, a PID regulator for the series field (separately) winding, and a calculator of the rotor current. Chopper 2 regulates the field current in two zones by varying the field voltage in the first zone with the help of the PID 2 regulator, the field current is exactly as the rotor current, meaning $i_e=i_r$. In the second zone with field leakining, with the help of the PID 3 regulator prescribed speed is compared with the real one, and lowers the field voltage if necessary.

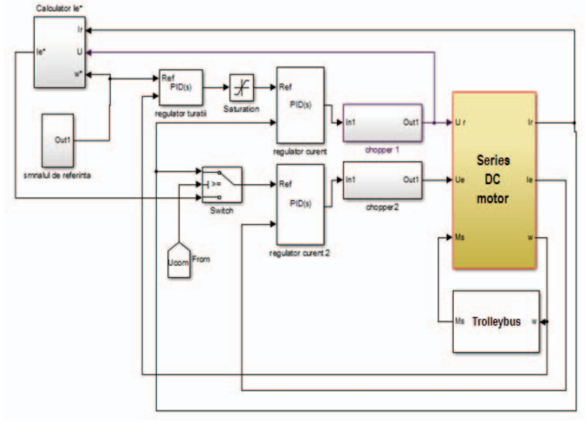

Fig 6. Simulink model of control traction system

The mathematical model of the motor and its mechanical parts are introduced in respective subsystems for easing the comprehension of the scheme. This model corresponds to the physical model represented above.

Key block in this modeling is PID controller's (2DOF). The PID Controller (2DOF) block generates an output signal based on the difference between a reference signal and a measured system output. The block computes a weighted difference signal for each of the proportional, integral, and derivative actions according to the set point weights you specify. The block output is the sum of the proportional, integral, and derivative actions on the respective difference signals, where each action is weighted according to the gain parameters. A first-order pole filters the derivative action. Controller gains are tunable either manually or automatically. Automatic tuning requires Simulink Control Design™ software (PID Tuner or SISO Design Tool) [10].

Configurable options in the PID Controller (2DOF) block include:

- Controller type (PID, PI, or PD)
- Controller form (Parallel or Ideal)
- Time domain (continuous or discrete)
- Initial conditions and reset trigger
- Output saturation limits and built-in anti-windup mechanism
- Signal tracking for bumpless control transfer and multiloop control

In one common implementation, the PID Controller (2DOF) block operates in the feed forward path of the feedback loop. The block receives a reference signal at the Ref input and a measured system output at the other input.

Controller adjustment can be performed by clicking the TUNE button. Controller's subsystem calculates the transfer function of the system, then it plots a graph with response time (gray line) [10]. This time can be adjusted with slider, after the controller parameters are recalculated. In Fig.6 is shown the speed controller adjustment window. The window shows controller coefficients and qualitative indices of adjustment, so it is possible online tuning of parameters.

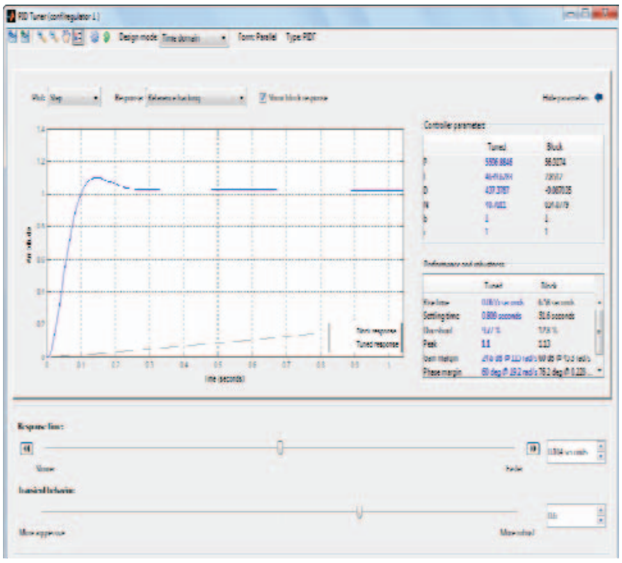

Fig 7. Controller adjustment window

For practical use of this model is necessary to know controller parameter value. The coefficients of controllers are shown in the tab.1.

After tuning of the controllers, the control system provides an override of 1.8% and 0.001s respectively for speed and currents, and a rise time to 0.15 s and 0.5 s for the same variables.

TABLE I.
NUMERICAL VALUES OF PID CONTROLLERS COEFFICIENTS

Regu-latorul	Parametrii		
	P	*I*	*D*
PID1	4.3	2.6	-2.5
PID2	0.06	19.76	0
PID3	0.5	0.9	0

V. SIMULATION OF THE TRACTION SISTEM WITH DC MOTOR AND SEPARATE FIELD CONTROL

Based on the developed mathematical model was simulated trolleybus traction developed driven by Series DC motor. Figure 8 shows the simulation results of transient processes at startup with adjustment only one armature voltage Ur . Current of series field Ie follows exactly the curve of armature current Ir. Simultaneously, there is a 300A current limit value. Voltage of series winding has the same character as field current Ie. Calculated speed w of motor almost coincide with the speed required w * and for this method does not exceed 200 s-1.

In fig.9 are shown the same variables in starting of the traction system with a separately windings control of Series MCC into two control zones. In the first zone occurs the speed control by varying armature voltage, the series field current Ie follows closely the armature current Ir. In the second zone is used field weakening for speed control by decreasing of the field current compared to the rotor current. Due to the field weakening the motor speed rises above 300 s-1.

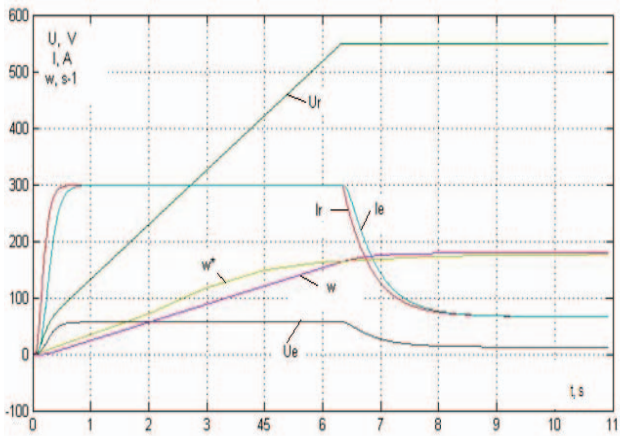

Fig 8. Dynamic characteristics of the traction system for only armature control

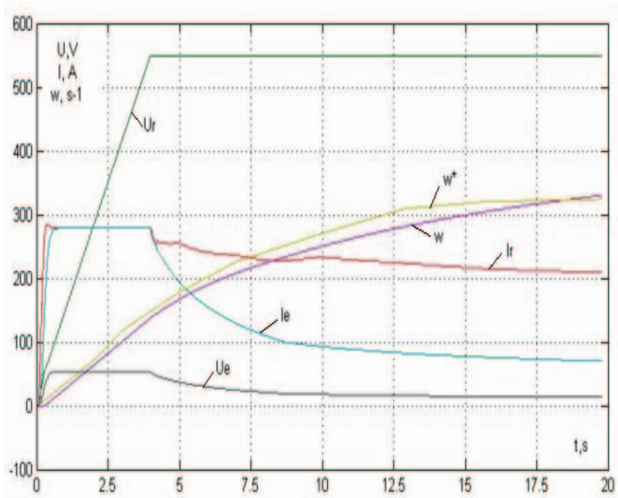

Fig 9. Dynamic characteristics of the control system for separately armature and series field control of Series DC motor

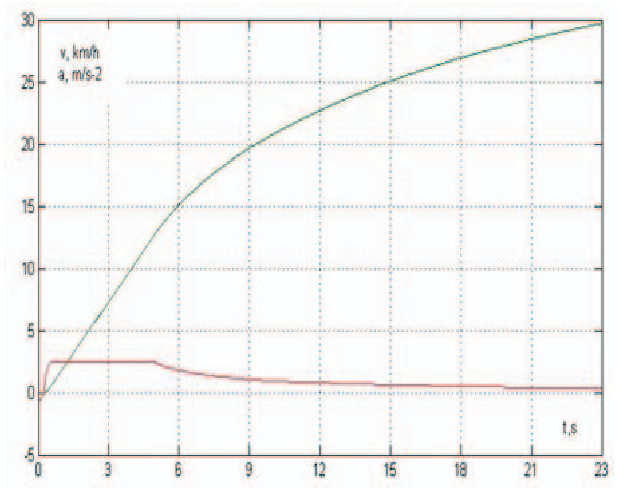

Fig 10. Translation speed and acceleration for separately armature and series field control of Series DC motor

Separately windings control of Series/Compound DC motor allow improvement of the dynamics trolley, rod ensures smooth walking speed and acceleration Fig.11, which results in increasing the mechanical reliability and passenger comfort.

Compared with the traditional method of field weakening Fig.11 proposed separately series field control of Series/Compound DC motors allows eliminate current shocks Fig.12.

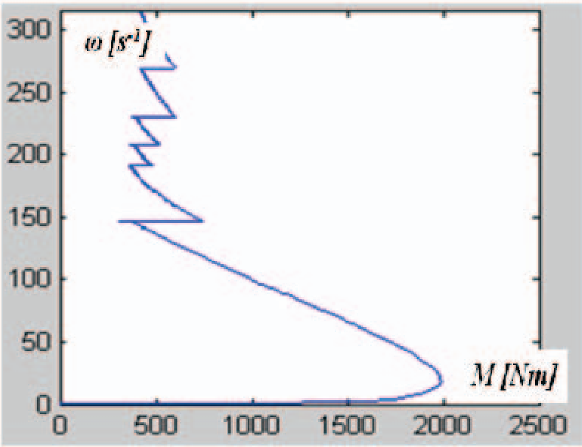

Fig..11. Mechanical characteristic of Compound DC motor with the classic field weakening

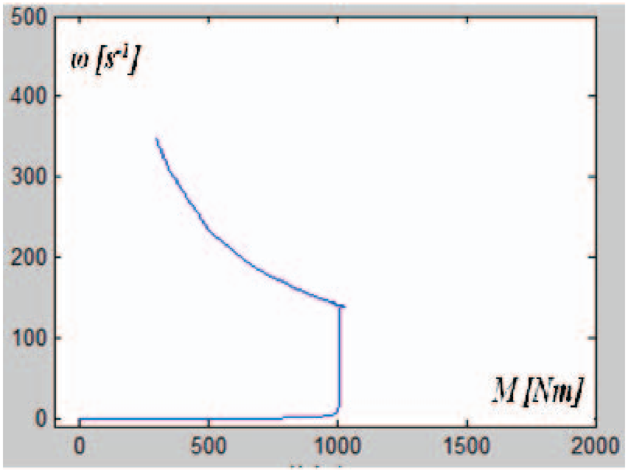

Fig..12. Mechanical characteristic of Compound DC motor with separately series field control

Separate windings control of the Series DC motor allows considerable improvement system dynamics, increases passenger comfort and reliability of the mechanical Fig.13.

VI. Conclusion

Separately windings control of the Series/Compound DC Motor allows smooth adjustment speed in both zones. At the same time, mechanical characteristic retains hyperbolic shape.

For this method was developed a control system with inner current control loop and outer speed loop. The results demonstrate the possibility of using the speed loop. By using of default tools of the Matlab-Simulink can simple tuning of the PID controllers. The proposed method permits to raise performance indicators of control system.

Separately windings control of the Series/Compound DC Motor can be recommended for use in electric vehicles traction systems.

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