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MRAS speed estimator with fuzzy and PI stator resistance adaptation for sensorless induction motor drives using RT-lab☆

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Rotor speed;
Stator resistance;
RT Lab

Summary This paper presents a real-time simulation study of Model Reference Adaptive System based rotor speed estimator with parallel stator resistance adaptation mechanism for speed sensorless induction motor drive. Both, the traditional Proportional Integral and Fuzzy logic based control mechanisms are utilised for stator resistance adaptation, while, the rotor speed is estimated parallely by means of Proportional Integral based mechanism. The estimator's response to dynamic changes in Load perturbation and doubling of the nominal value of the actual stator resistance of the motor is observed. The superiority of the fuzzy based stator resistance adaptation in the Model Reference Adaptive System estimator is proved through results validated in real-time. The purpose of employing a fairly new real-time platform is to reduce the test and prototype time. The model is initially built using Matlab/Simulink blocksets and the results are validated in real time using RT-Lab. The RT-lab blocksets are integrated into the Simulink model and then executed in real-time using the OP-4500 target developed by Opal-RT. The real-time simulation results are observed in the workstation.

Introduction

Presently, Indirect Field Oriented Control of induction motor drives has been employed in a wide range of applications [5]. As the torque and flux requests were needed as inputs to the indirect vector control mechanism, the speed encoders were commonly used. The inherent disadvantage associated with the speed encoders were high cost, additional electronics and mounting space. Therefore, in order to do away with this constraint, sensorless vector control came into prominence [3]. Instead of using a speed encoder, the rotor speed was estimated by either making use of the machine model or the magnetic saliencies of the machine. Among these, the machine model based speed estimation techniques were easy to implement, occupied less computational space and were devoid of measurement delays associated with

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i^S_{ds}, i^S_{qs}	d and q axis stator currents in stationary reference frame
$\hat{\psi}^S_{qrV}, \hat{\psi}^S_{drV}$	d and q axis voltage model rotor flux linkage in stationary reference frame
$\hat{\psi}^S_{qrI}, \hat{\psi}^S_{drI}$	d and q axis current model rotor flux linkage in stationary reference frame
L_r, L_m, L_s, σ	rotor, magnetising and stator inductance, reactance
$R_S, \hat{R}_S$	actual and estimated stator resistances
$\omega_r, \hat{\omega}_r, T_r$	actual and estimated rotor speeds, rotor time constant
K_p, K_I	proportional and integral gains

measurement techniques utilising the magnetic saliencies [6]. The only problem with the former was parameter dependency. Hence, many model based estimation techniques adapted the parameters online and also were used for joint state estimation [1,2,8,9].

The purpose of a real time simulation platform is to ensure the computer model runs at the same rate as the actual physical system. The processing of the inputs, model calculations and the outputs are done within a required time step. The real time technologies are time critical and are used in several industrial applications catering to motor drives and control, power systems, robotics, gaming, etc. RT-Lab, developed by Opal-RT, is more popularly used by virtue of its flexibility and can be utilised in any simulation or control system based approach [11]. The estimator is built in Offline simulink environment present in the Host computer, while the Opal-RT based OP4500 Simulation target performs simulation in real-time. The Real-time simulator mainly comprises of a real time distributed simulation package (RT-Lab), to execute simulink models on a Host PC, and algorithmic toolboxes which are used for fixed time-step simulation of controllers. In this paper, by treating the external load torque disturbance as a model disturbance, and by doubling the nominal value of the actual stator resistance of the motor, the dynamic performance of the estimator for changes in the above parameters is realised for both PI and Fuzzy based Stator resistance adaptation mechanisms.

MRAS based adaptive speed estimation schemes

In large, non linear dynamic systems, there will be very high variation in parameters and considerable disturbances would be introduced. Therefore, an ordinary feedback system will not give satisfactory performance. It is essential to introduce certain adaptive properties, so that, they compensate the variations in parameter, process dynamics or disturbances. Thereby, the performance of the system is optimised. As a result, adaptive speed estimation schemes fed from the machine model were popular and occupied considerable research. The Model Reference Adaptive Systems or MRAS, formed the basic configuration of Adaptive speed estimation schemes [4,7,10]. It comprises of two mathematical models, the reference model, which signifies the desired performance of the system and the adjustable model (or the adaptive model), which signifies the process. It also has an adaptive mechanism, which is used to converge the behaviour of the process with the desired performance. The estimated parameter is fed back to the adjustable model and the controller parameters are tuned in such a way that the error between the two models converges to zero and the estimated value equals the real.

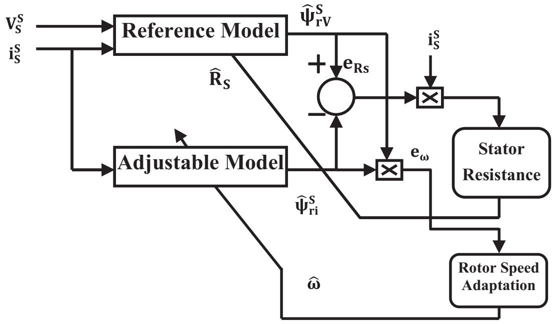

Figure 1 Mutual MRAS based stator resistance and rotor speed adaptation.

Authors of [12] developed a simultaneous stator resistance and speed adaptation mechanism based on mutual MRAS scheme, where the difference in amplitudes of the estimated rotor flux vectors is used to estimate the stator resistance. The concept of mutual MRAS is based on the ability of the reference and the adjustable models to switch roles depending upon the quantity to be adapted. The above mechanism is illustrated in Fig. 1.

Structure of mutual MRAS estimator

The estimator is constructed in the Stationary reference frame and is depicted by the following equations [12]:

$$\hat{\psi}^S_{qrV} = \frac{L_r}{L_m}\left[\int (V^S_{qs} - \hat{R}_s i^s_{qs} - \sigma L_s i^s_{qs})\,dt\right] \quad (1)$$

$$\hat{\psi}^S_{drV} = \frac{L_r}{L_m}\left[\int (V^S_{ds} - \hat{R}_s i^s_{ds} - \sigma L_s i^s_{ds})\,dt\right] \quad (2)$$

where $\sigma = 1 - \frac{L_m^2}{L_s L_r}$

$$p\hat{\psi}^s_{qrI} = \left(\frac{-1}{T_r}\right)\hat{\psi}^s_{qrI} + \hat{\omega}_r\hat{\psi}^s_{drI} + \left(\frac{L_m}{T_r}\right) i^s_{qs} \quad (3)$$

$$p\hat{\psi}^s_{drI} = \left(\frac{-1}{T_r}\right)\hat{\psi}^s_{drI} + \hat{\omega}_r\hat{\psi}^s_{qrI} + \left(\frac{L_m}{T_r}\right) i^s_{ds} \quad (4)$$

Parallel adaptation mechanism for rotor speed and stator resistance

The Popov's stability criterion is used to ensure asymptotic stability of the non linear system:

$$S = \int_0^{t_0} \varepsilon^T W dt \geq -\gamma^2, \quad \text{for all} \quad t_0 \quad (5)$$

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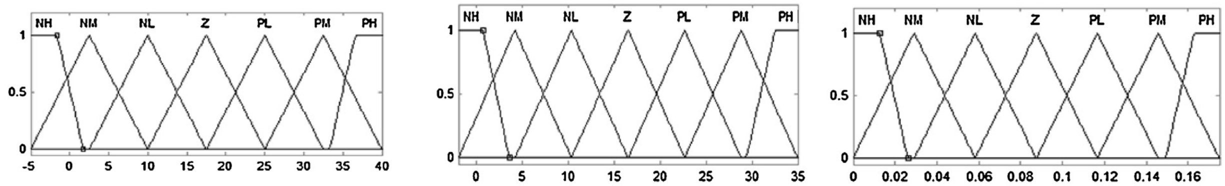

(a) (b) (c)

Figure 2 Membership functions for the Fuzzy estimator (a), stator resistance error (b), change in stator resistance error (c) estimated stator resistance.

where $\varepsilon^T = \left[\varepsilon_{drI} \quad \varepsilon_{QrI} \quad \varepsilon_{drV} \quad \varepsilon_{QrV}\right]$, and the non linear matrix is denoted by 'W' given as:

$$W = \begin{bmatrix} -\Delta\omega_r \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} & \begin{matrix} 0 & 0 \\ 0 & 0 \end{matrix} \\ \begin{matrix} 0 & 0 \\ 0 & 0 \end{matrix} & \dfrac{L_r}{L_m}\Delta R_S \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \end{bmatrix} \begin{matrix} \hat{\psi}_{drI} \\ \hat{\psi}_{qrI} \\ i_{ds} \\ i_{qs} \end{matrix} \tag{6}$$

where $J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$, and $I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$ and $\Delta\omega_r = \omega_r - \hat{\omega}_r$ and $\Delta R_S = R_S - \hat{R}_S$;

The non linear matrix in the reduced form is given by:

$$W = \begin{bmatrix} -\Delta\omega_r J & 0 \\ 0 & \dfrac{L_r}{L_m}\Delta R_S I \end{bmatrix} \begin{matrix} \hat{\psi}_{rI} \\ i_S \end{matrix} \tag{7}$$

The Popov's stability criterion can be resolved into two inequalities as follows:

$$S = \lambda_1 + k\lambda_2 \tag{8}$$

Here $\lambda_1 \geq -\gamma_1^2$ and $\lambda_2 \geq -\gamma_2^2$ and $k = (L_r/L_m)$ and γ_1 and γ_2 are positive real constants. The rotor speed is estimated from the first equality and compensated in the current model. Therefore, we have:

$$\lambda_1 = -\int_0^{t_0} \Delta\omega_r(\varepsilon_I^T J \hat{\psi}_{rI})\, dt \tag{9}$$

Here $\varepsilon_I = \hat{\psi}_{rV}^S - \psi_{rI}^S$, and on solving,

$$\varepsilon_I^T J \hat{\psi}_{rI}^S = [\hat{\psi}_{drV}\hat{\psi}_{qrI} + \hat{\psi}_{qrV}\hat{\psi}_{drI}] = e_\omega \tag{10}$$

where e_ω, is the rotor speed error. Using PI control based mechanism, the estimated rotor speed $\hat{\omega}_r$ is obtained.

$$\hat{\omega}_r = \left\{K_P + \frac{K_I}{S}\right\} e_\omega \tag{11}$$

From the second inequality, the stator resistance is estimated and compensated in the voltage model. Now, the current model acts as reference model. Therefore, we have:

$$\lambda_2 = \int_0^{t_0} \Delta R_S\left(\varepsilon_V^T i_S^S\right) dt \tag{12}$$

where $\varepsilon_V = \hat{\psi}_{rI}^S - \psi_{rV}^S$, on solving,

$$\varepsilon_V^T i_S^S = i_{ds}(\hat{\psi}_{drV} - \hat{\psi}_{drI}) + i_{qs}(\hat{\psi}_{qrV} - \hat{\psi}_{qrI}) = e_{Rs} \tag{13}$$

Table 1 Fuzzy rule matrix for stator resistance adaptation.

		e_{Rs}						
		NH	NM	NL	Z	PL	PM	PH
	NH	NH	NH	NH	NH	NM	NL	Z
	NM	NH	NH	NH	NM	Z	Z	PL
	NL	NH	NH	NM	Z	Z	Z	PM
Δe_{Rs}	Z	NH	NM	Z	Z	Z	PM	PH
	PL	NM	Z	Z	Z	PM	PH	PH
	PM	Z	Z	Z	PM	PH	PH	PH
	PH	Z	PL	PM	PH	PH	PH	PH

where e_{Rs}, is the stator resistance error.

PI based stator resistance adaptation

$$\hat{R}_S = \left\{K_P + \frac{K_I}{S}\right\} e_{Rs} \tag{14}$$

where K_P and K_I are the proportional and integral gains and $\hat{R}_S$ is the stator resistance.

Fuzzy logic based adaptation of stator resistance

The inputs to the fuzzy based scheme are the change in stator resistance error and the stator resistance error. The estimated stator resistance is the output and the fuzzification stage comprises of seven segments namely NH, NM, NL, Z, PL, PM, PH corresponding to negative high, negative medium, negative low, zero, positive low, positive medium and positive high respectively. The membership functions used are shown below in Fig. 2. The rule base matrix (7*7) employing 49 rules is shown in Table 1. The control range is between −5 and +40 for the stator resistance error, −2 and +35 for the change in error and 0 and +0.175 for the estimated stator resistance.

Both, the speed estimate and the stator resistance estimate are used for obtaining the electromagnetic torque as shown:

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r[\hat{\psi}_{drV} i_{qs}^s - \hat{\psi}_{qrV} i_{ds}^s]} \tag{15}$$

Real-time simulation results: analysis and discussion

The model is built offline in Matlab/Simulink, present in the Host computer. The offline simulated results are recorded and then, the simulink model is integrated with RT-Lab

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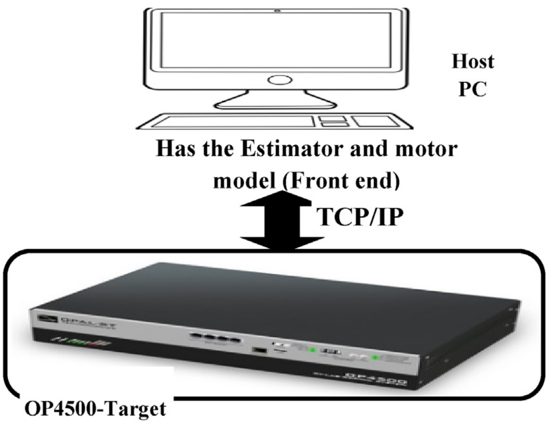
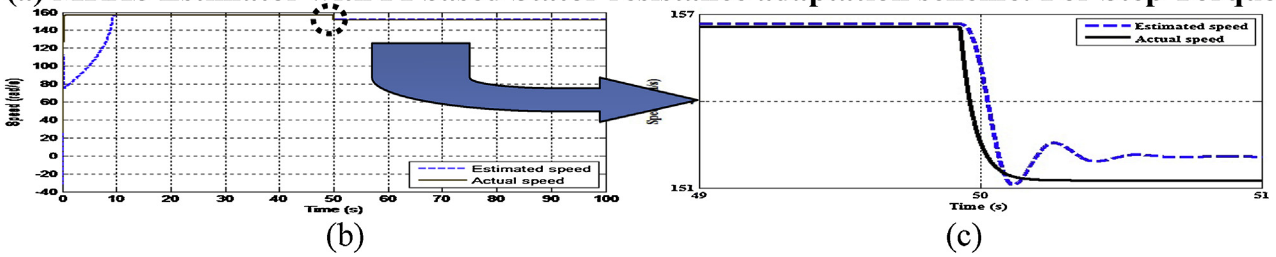


Figure 3 OP4500-RT-Lab based real-time simulation platform.

blocksets and compiled in Real-Time. The RT-Lab based real-time platform is shown in Fig. 3. The fixed time step used for real-time simulation is 50e−6 s. The tracking performance for different stator resistance based adaptation mechanisms is realised for the following cases:

(i) Step Torque — initially at no load, after a fixed time interval, to rated load of 150 Nm.
(ii) At No Load, by doubling the nominal value of the actual Stator resistance of the motor.

While observing the real-time simulated results, the superiority of Fuzzy stator resistance compensation mechanism is clearly seen in the way the estimated speed and electromagnetic torque track their respective original values. The zoomed versions of the results are presented in select cases to add more clarity and distinctness. Fig. 4. shows the tracking performance of the estimated speed in real-time environment for PI based stator resistance compensation. Though the speed converges to the actual value, in real-time, the time taken to settle down is more (approximately 10 s) as compared to the Fuzzy stator resistance compensation, where there is almost near accurate tracking of the estimated speed as shown in Fig. 8. The same can be observed even when the nominal value of the actual stator resistance of the motor is doubled, as shown in Figs. 6 and 10. Ideally, for a drive system, the load torque must equal the electromagnetic torque, it is observed in Figs. 5 and 7, that the estimated electromagnetic torque, more or less, tracks the profile of the Load torque, with a slightly higher magnitude to take into account the frictional


(a) MRAS Estimator with PI based Stator resistance adaptation scheme: For Step Torque

(b) (c)

Figure 4 (a) Real-Time Estimated Rotor speed and (b) Zoomed version of (a).

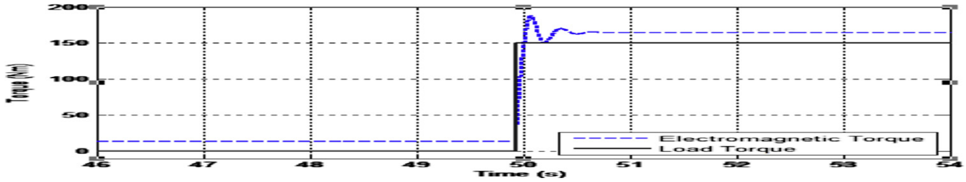
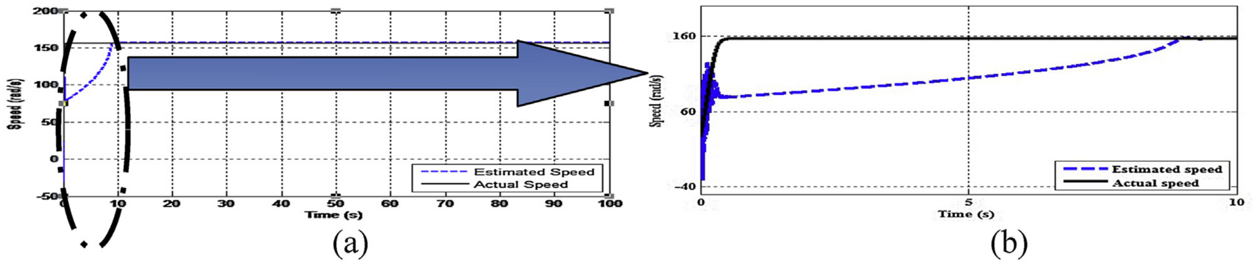


Figure 5 Real-Time Estimated Electromagnetic torque.


(ii) Doubling the nominal value of the actual stator resistance at No Load:

(a) (b)

Figure 6 (a) Real-Time Estimated Rotor speed and (b) Zoomed version of (a).

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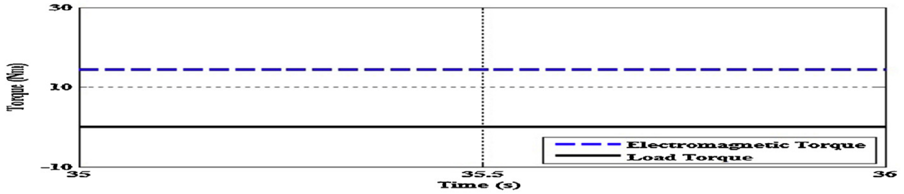
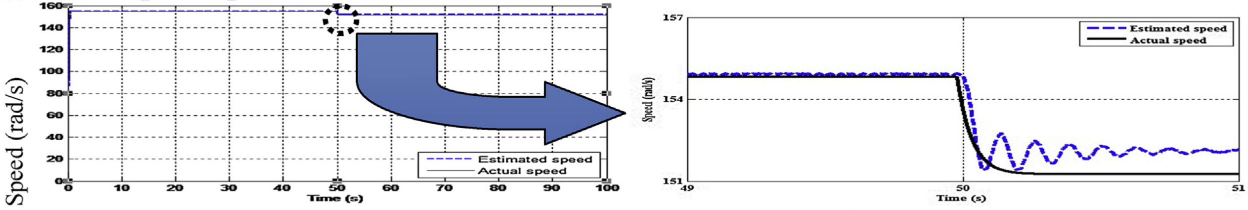


Figure 7 Real-Time Estimated Electromagnetic torque.

(b) MRAS Speed Estimator with Fuzzy Logic based Stator resistance adaptation scheme:

(i) For Step Torque



(a) (b)

Figure 8 (a) Real-Time Estimated Rotor speed and (b) Zoomed version of (a).

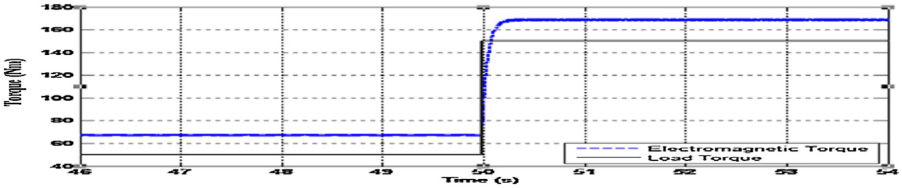
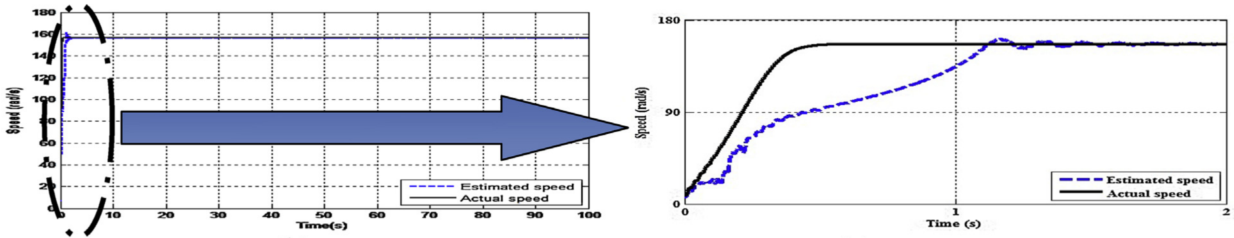


Figure 9 Real-Time Estimated Electromagnetic torque.

(ii) Doubling the nominal value of the actual stator resistance at No Load



(b) (c)

Figure 10 (a) Offline and (b) Real-Time Estimated Rotor speed (c) Zoomed version of (b).

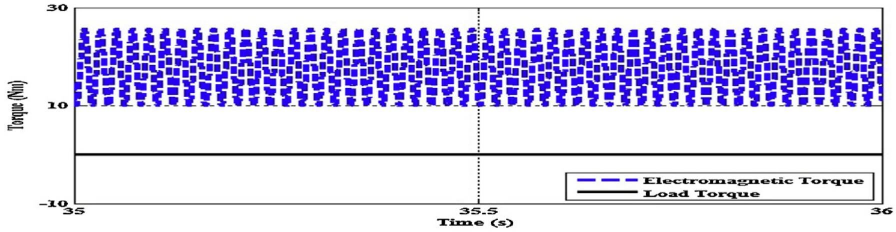


Figure 11 (a) Offline and (b) Real-Time Estimated Electromagnetic torque.

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and mechanical losses. However, in Figs. 9 and 11, a small percentage of torque oscillations can be observed, which are constant. This can be attributed to the presence of pulsations in the *q*-axis component of the stator current as the estimated torque is a function of the voltage model rotor fluxes and the *d*-axis and *q*-axis stator currents. Also, the *q*-axis stator current is responsible for torque production. The analysis is carried out in motoring mode at speeds ranging around the base synchronous value.

Conclusion

The effectiveness of the Fuzzy based stator resistance adaptation mechanism over the conventional PI based stator resistance adaptation mechanism in the MRAS estimator is proven by the real-time simulated results using RT-Lab. The validation in a comparatively new time critical platform reduced the testing time, added more clarity and corresponded to the performance of the actual physical model. The above concept utilises the idea of Mutual MRAS based parallel rotor speed and stator resistance adaptation. The same can be extended to other means of real-time testing, which include rapid control prototyping and Hardware in the Loop.

Appendix.

The motor ratings and the parameters considered are as follows: A 50HP, three-phase, 415 V, 50 Hz, star connected, four-pole induction motor with equivalent parameters: $R_S = 0.087\,\Omega$, $R_r = 0.228\,\Omega$, $L_s = L_r = 0.8\,\text{mH}$, $L_m = 34.7\,\text{mH}$, Inertia, $J = 1.662\,\text{kgm}^2$, friction factor = 0.1.

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