Steady State Operation of Self-Excited Induction Generator with Varying Wind Speeds

K.S. Sandhu and S.P.Jain

Abstract**—**In contrast to conventional generators, self-excited induction generators are found to be most suitable machines for wind energy conversion in remote and windy areas due to many advantages over grid connected machines. However such machines exhibits poor performance in terms of voltage and frequency under frequent variations of operating speeds, which is a common feature in wind energy conversion. In this paper an attempt has been made to present a simple model to control the output voltage and frequency in case of self-excited induction generator under such operating conditions. It is realized that rotor resistance control for a wound rotor machine results in to a constant voltage constant frequency operation. Simulated results as obtained have been compared with experimental results on two test machines and found to be in close agreement.

Key-Words**—**Induction Generator, Renewable Generation, Steady State Analysis (SSA), Self- Excited Induction Generator, Wind Energy Generation.

NOMENCLATURE

a	per unit frequency
b	per unit speed
C	excitation capacitance per phase
E_1	air gap voltage per phase at rated frequency
E_2	rotor emf per phase referred to stator
E_a	air gap voltage per phase= aE_1
f	rated frequency
I_1	stator current per phase
I_2	rotor current per phase, referred to stator
I_L	load current per phase
I_m	magnetizing current per phase
P_{out}	output power
R	load resistance per phase
R_1	stator resistance per phase
R_2	rotor resistance per phase, referred to stator
R_{ext}	external rotor resistance per phase, referred to stator
s	generator slip
V	terminal voltage per phase
X_1	stator reactance per phase
X_2	rotor reactance per phase, referred to stator
X_c	capacitive reactance due to C at rated frequency
X_m	magnetizing reactance per phase at rated frequency

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I. INTRODUCTION

Continuous reduction of conventional sources of energy as well as growing power demand has diverted the attention of scientists towards the non-conventional sources of energy such as wind energy, solar energy, tidal energy, geothermal energy and biogas. Renewal energy is expected to create maximum impact in the production of electricity. Projections indicate that by the end of the first decade of the new century, it would be cost effective to generate and supply renewable electricity. Besides grid supply augmentation, renewable electric technologies offer possibilities of distributed generation at or near points of use, which can reduce peak loads and save on costly up gradation and maintenance of transmission and distribution networks.

Out of these wind energy is the fastest growing area of all renewable energy resources and is attractive and viable. Man is utilizing wind power for the last 3000 years. Earlier it was used to provide mechanical power to pump water or to grind grains. In early 1970s with a sharp rise in oil prices, interest in wind power reemerged. However by the end of 1990s, wind power became as one of the sustainable energy resource. No other renewable energy based electricity producing technology has attained the same level of maturity as wind power. There are no major technical barriers to large-scale penetration of wind power. It also offers an attractive investment option to the private sector for power generation.

It is observed that winds carry enormous amount of energy and could meet sufficient energy needs of the world. The regions in which strong winds prevail for a sufficient time during the year may use wind energy profitable for different purposes. It has been found that cost of wind generation is comparable to that of hydro and thermal plants. There is a little doubt that while the cost of wind generation would be even lower in the coming years; the prices of fossil fuels used by thermal plants would definitely go up. In view of high capital constructional cost hydel power would be dearer too. In addition to this wind energy generation provides a clean and pollution free environment. It does not lead to global warming and ozone depletion. No hazardous waste is created. Further a wind turbine generator may be a very worthwhile proposition for an isolated and remote area. Application of induction generators [1-14] is well known to extract the wind energy through turbines. An induction motor connected to constant voltage, constant frequency supply system behaves as a generator if made to run at a speed higher than synchronous speed. In such an operation, the exciting current is provided by the supply system, to which the machine is connected and the frequency of the voltage generated by the induction generator is the same as that of supply system.

It was also well established that an induction machine might be run as a generator by connecting suitable capacitors across stator terminals to provide excitation. In such an arrangement, the frequency of the generated voltage is not fixed but beside other factors depends upon the speed of the prime mover. Self-excited induction generators (SEIG) are found to be most suitable for many applications including wind energy conversion systems. Such generators may also be used in the remote areas in the absence of grid. These machines have many advantages such as brush less construction (squirrel-cage rotor), reduced size, absence of DC power supply for excitation as in conventional generators, reduced maintenance cost, self short-circuit protection capability and no synchronizing problem. Steady state equivalent circuit representation and mathematical modeling is required to evaluate the steady-state performance of a SEIG feeding a specific load. In order to estimate the performance of a SEIG, researchers have made use of the conventional equivalent circuit of an induction motor. Steady state modeling of grid connected induction generator using saturated magnetizing reactance has been described in [1]. Power quality effects in case of SEIG are investigated by [2]. Whereas, [3] investigated the stability aspects of wind driven induction generator. Some of the researchers [4-9] used the impedance model, and a few [10-13] used the admittance-based model for to estimate the performance of these machines. However it has been felt that the old conventional equivalent circuit model, in the absence of an active source, does not effectively correspond to generator operation. Therefore [14] suggested a new circuit model for the representation of induction generator.

For windmill drives, the speed of the induction machine depends upon the velocity, volume and the direction of wind. These parameters may very in wide limits. It is found that such machine exhibits poor performance in terms of voltage and frequency under frequent variations of operating speeds, which is a common feature in wind energy conversion. It is therefore, desirable to investigate the behaviour of a self-excited induction generator suitable for windmill drive under controlled and uncontrolled speed operation. It is realized that such variations in operating speeds may be compensated by proper handling of load and rotor resistance. Therefore, in this paper an attempt has been made to propose a simple model for the steady state analysis and control of self-excited induction generators operating with fluctuations in operating speed. Simulated results as obtained have been compared with experimental results on a test machine and found to be in close agreement.

In the following section two operational aspects have been considered to study the behavior of an induction generator. The two operating modes accounted for studies are;

- Variable voltage constant frequency operation
- Constant voltage constant frequency operation

II. CONTROLLED SPEED OPERATION

The steady-state operation of wound rotor self-excited generator may be analyzed by using an equivalent circuit representation as shown in Fig. 1.

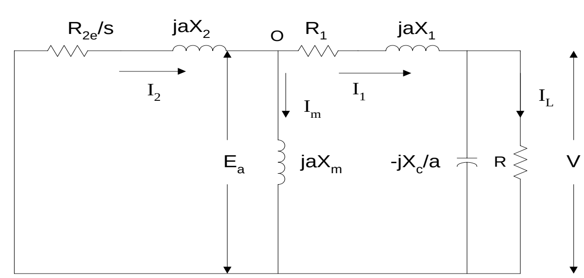

Fig. 1. Per phase equivalent circuit representation for wound rotor Self-excited induction generator.

Where $R_{2e} = R_2 + R_{ext}$

Analysis of circuit at node O gives;

$$\frac{s\,R_{2e}}{R_{2e}^2 + s^2 a^2 X_2^2} - \frac{R_{1L}}{R_{1L}^2 + X_{1L}^2} = 0 \qquad (1)$$

$$\frac{s^2 a X_2}{R_{2e}^2 + s^2 a^2 X_2^2} - \frac{1}{a X_m} - \frac{X_{1L}}{R_{1L}^2 + X_{1L}^2} = 0 \qquad (2)$$

Solution of (1) gives;

$$A_2 s^2 + A_1 s + A_0 = 0 \qquad (3)$$

where,

$$A_2 = a^2 X_2^2 R_{1L}$$
$$A_1 = -R_{2e}\left(R_{1L}^2 + X_{1L}^2\right)$$
$$A_0 = R_{1L} R_{2e}^2$$

$$R_{1L} = R_1 + R_L$$
$$X_{1L} = aX_1 - X_L$$
$$R_L = \frac{R X_c^2}{a^2 R^2 + X_c^2}$$
$$X_L = \frac{a R^2 X_c}{a^2 R^2 + X_c^2}$$

and

$$b = a\,(1 + s) \qquad (4)$$

Equation (3) & (4) may be used to determine the operating speed which results in to desired generated frequency with load resistance & excitation capacitance known. Out of two values of slip as given by (3) only smaller one is relevant in generating mode. Solution of (2) gives;

$$X_m = \left[\frac{R_{2e}\left(R_{1L}^2 + X_{1L}^2\right)}{s a^2 X_2 R_{1L} + a R_{2e} X_{1L}}\right] \qquad (5)$$

Equation (5) may be used to determine the effective value of X_m i.e the magnetizing reactance under given operating conditions. X_m as obtained may be used to determine the value of air gap voltage' E_1 ' using Appendix-I &II.

In order to generate the rated frequency, modeling may be used to determine the operating speed for given value of load resistance, excitation capacitance. However generated voltage will vary in accordance to operating speed of the machine. Therefore controlled speed operation results in to the constant frequency variable voltage operation for any load condition. Further as shown in Fig. 2, a transformer with additional source of reactive power may be used to generate constant voltage constant frequency output.

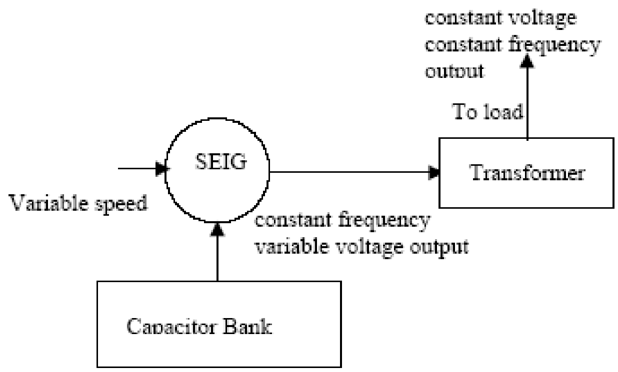

Fig. 2 Constant voltage constant frequency operation

III. UNCONTROLLED SPEED OPERATION

Equation (1) after rearrangement gives;

$$K_2 R_{2e}^2 + K_1 R_{2e} + K_0 = 0 \qquad (6)$$

Where,

$$K_2 = -R_{1L}$$
$$K_1 = s\left(R_{1L}^2 + X_{1L}^2\right)$$
$$K_0 = -a^2 s^2 R_{1L} X_2^2$$

Values of R_{1L}, X_{1L}, R_L & X_L are same as defined in the previous section. Equation (4) and (6) may be used to determine the rotor resistance to obtain desired frequency for any operating speed. This value of rotor resistance with new value of slip corresponding to operating speed is used in (5) to determine the effective value of X_m. Magnetizing reactance as obtained may be used to determine the value of air gap voltage' E_1 ' using Appendix-I & II. This gives an estimation of additional rotor resistance to maintain the terminal voltage and frequency. Any change in operating speed may be compensated by proper handling of rotor resistance, which is possible in case of wound rotor induction machines only.

IV. RESULTS & DISCUSSIONS

Fig. 3 & Fig. 8 shows the comparison of computed and experimental results on test machine-1 [Appendix-I]. Comparison is made for different values of excitation capacitance and load resistance. Closeness between the computed and experimental results proves the validity of the proposed modeling.

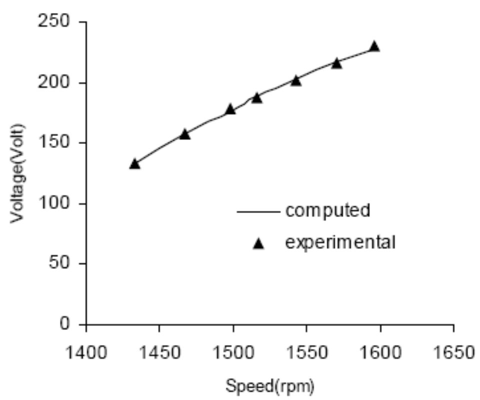

Fig. 3 Variation of terminal voltage with operating speed, C=36 micro-farad, R=160 ohm

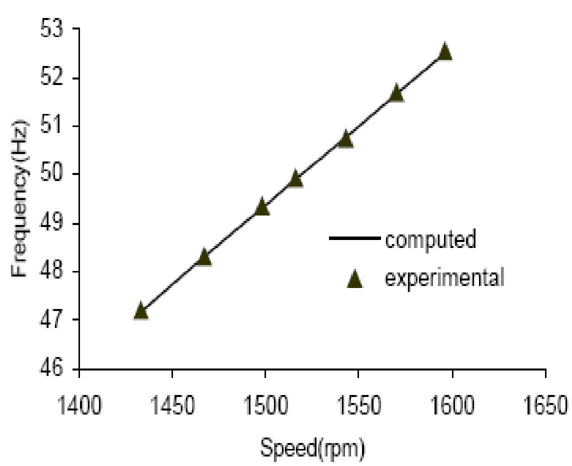

Fig. 4 Variation of generated frequency with operating speed, C=36 micro-farad, R=160 ohm

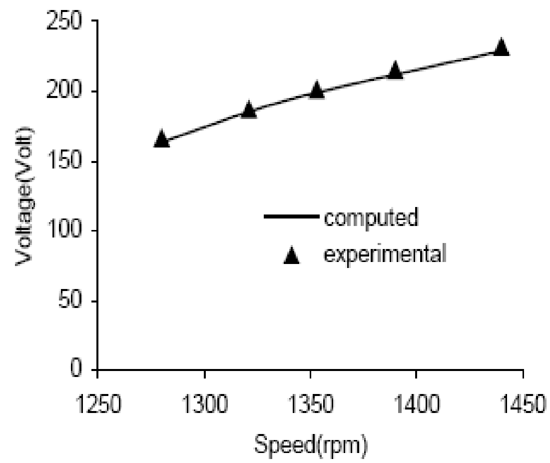

Fig. 5 Variation of terminal voltage with operating speed, C=51 micro-farad, R=160 ohm

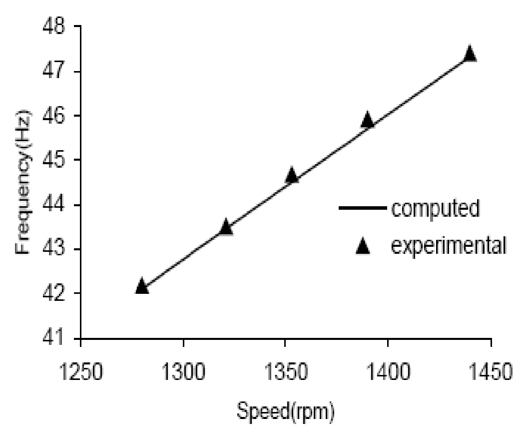

Fig. 6 Variation of generated frequency with operating speed, C=51 micro-farad, R=160 ohm

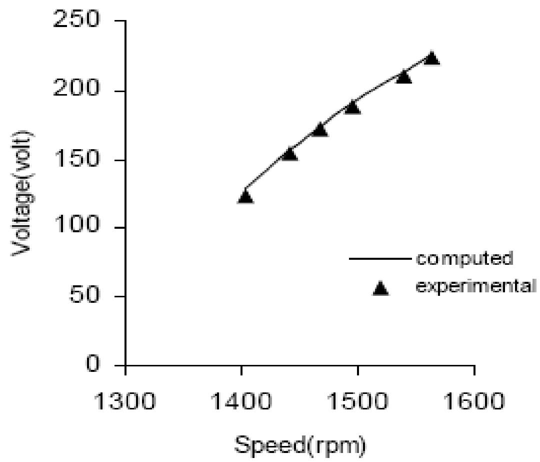

Fig. 7 Variation of terminal voltage with operating speed, C=36 micro-farad, R=220 ohm

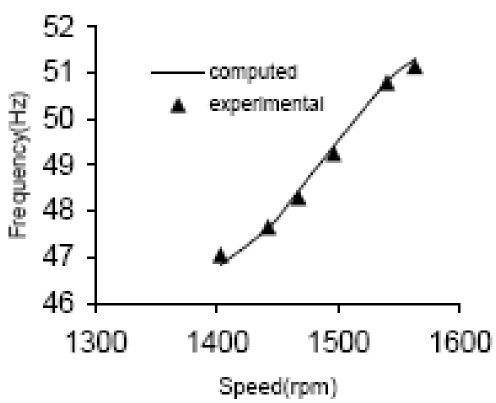

Fig. 8 Variation of generated frequency with operating speed, C=36 micro-farad, R=220 ohm

Figure 9 and Figure 10 shows the comparison of computed and experimental results on another test machine-2 [Appendix-II]. Good agreement reconfirms the validity of approach adopted.

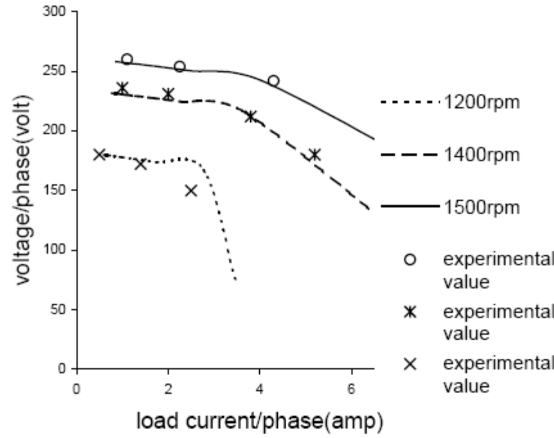

Fig. 9 Variation of terminal voltage with load, excitation capacitance=108 micro-farad

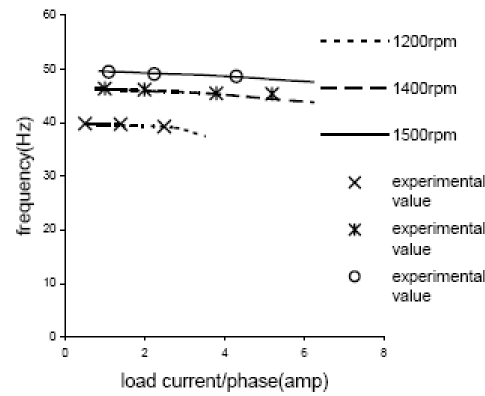

Fig. 10 Variation of generated frequency with load, excitation capacitance=108 micro-farad

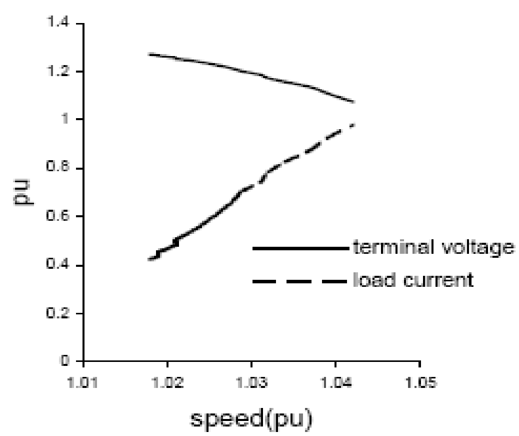

Fig. 11 Variation of terminal voltage & load with operating speed to maintain generated frequency

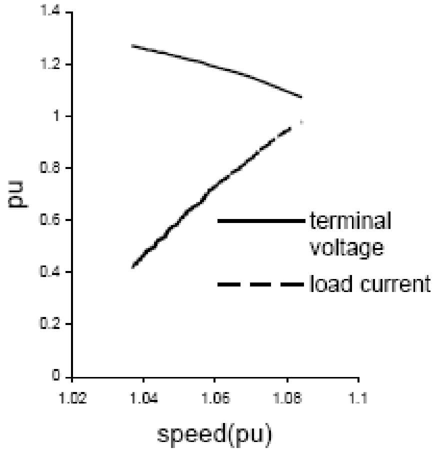

Fig. 12 Variation of terminal voltage & load with operating speed to maintain generated frequency

From Figs. 1 to 10, it is observed that any variation in the operating speed of the generator effects both generated frequency and terminal voltage. Generated frequency varies linearly with operating speed.

Table1 Estimation of external rotor resistance to maintain terminal voltage and frequency

Speed(pu)	Rotor Resistance(pu)	Terminal Voltage(pu)
C=1pu,R=1pu,a =1pu		
1.114	0.083	1.072
1.123	0.089	1.072
1.131	0.095	1.072
1.14	0.102	1.072
1.149	0.108	1.072
1.158	0.114	1.072
1.167	0.121	1.072
1.175	0.127	1.072
1.184	0.134	1.072
1.193	0.14	1.072
1.202	0.146	1.072
1.21	0.153	1.072
1.219	0.159	1.072
1.228	0.165	1.072
1.237	0.172	1.072

Table II Table1 Estimation of external rotor resistance to maintain terminal voltage and frequency

Speed(pu)	Rotor Resistance(pu)	Terminal Voltage(pu)
C=1.5pu,R=1pu,a =1pu		
1.148	0.083	1.259
1.159	0.089	1.259
1.171	0.095	1.259
1.182	0.102	1.259
1.194	0.108	1.259
1.205	0.114	1.259
1.216	0.121	1.259
1.228	0.127	1.259
1.239	0.134	1.259
1.251	0.14	1.259
1.262	0.146	1.259
1.274	0.153	1.259
1.285	0.159	1.259
1.296	0.165	1.259
1.308	0.172	1.259

This type of operation is suitable in case load is independent of frequency such as heating etc. However such a system cannot be used for frequency sensitive loads. In case of frequency sensitive loads it is desirable to operate the machine at constant frequency rather than at variable frequency.

For variable speed operations, proposed model may be used to develop a relation between the operating speed and load resistance for a constant value of excitation capacitance. With the help of this relation, the load resistance may be adjusted in a particular manner, resulting in a constant frequency operation as shown in Fig. 11 and Fig. 12 for test machine-1 [Appendix-I]. But it is observed that it results in to a variable voltage operation. This shortcoming as discussed in section II may be overcome by using a suitable transformer with additional source of reactive power.

Table 1 gives the estimated values of resistance required in rotor circuit to control the terminal voltage and frequency for variable speed operation on machine-2. This gives an opportunity to control the terminal conditions (Terminal Voltage=1.07pu & Generated Frequency=1.0pu) under unregulated speed operations for induction generator.

Similarly Table 2 shows the output voltage and generated frequency of machine-2 as 1.259pu and 1.0pu respectively. The difference between the two values for terminal voltage as appears in two tables is due to the variation in excitation capacitance. Thus there is a need to select the appropriate value of excitation capacitance to maintain the terminal voltage. Once machine is set to develop the rated voltage and frequency output with constant load for given value of excitation capacitance then rotor resistance control is capable to maintain the terminal conditions under wind speed variations.

V. CONCLUSION

In this paper an attempt has been made to propose a simple model for the steady state analysis of a self-excited induction generator (SEIG). Model is found to be suitable to maintain the generated frequency in controlled and uncontrolled speed operations of SEIG. Closeness between simulated and computed results on two test machines proves the validity of proposed modelling. Further this modelling gives an opportunity to control the terminal voltage and generated frequency by proper handling of external resistance in the rotor circuit. This will give an opportunity to operate the wound rotor induction generator with controlled output even in the absence of speed regulators.

APPENDIX I

Details of Machine 1

- Specifications

3 phase, 4- pole, 50 Hz, delta-connected, squirrel cage induction machine,
2.2 kW/3.0 hp, 230 V, 8.6 A

- Parameters

R_1 = 3.35 ohm, R_2 = 1.76 ohm, $X_1 = X_2$ = 4.85 ohm

- Base values

Base voltage = 230 V
Base current = 4.96 A
Base impedance = 46.32 ohm
Base capacitance = 68.71 μF
Base frequency = 50 Hz
Base speed = 1500 rpm

- Air gap voltage

The piecewise linearization of magnetization characteristics of machine-1gives

$$Xm < 82.292 \quad E_1 = 344.411 - 1.61Xm$$

$$95.569 > Xm \geq 82.292 \quad E_1 = 465.12 - 3.077Xm$$

$$108.00 > Xm \geq 95.569 \quad E_1 = 579.897 - 4.278Xm$$

$$Xm \geq 108.00 \quad E_1 = 0$$

APPENDIX-II

Details of Machine 2

- Specifications

3-phase, 4-pole, 50 Hz, wound rotor induction machine
7 kW,
Stator - 400/231 V, 14.7/25.4 A
Rotor (Y)- 220 V, 19.5 A

- Parameters

R_1=1.05 ohm, R_2=1.296 ohm, X_1=X_2=2.61 ohms

- Base values

Base voltage=231 volt
Base current=14.7 A
Base impedance=15.71 ohm
Base capacitance=202.6 μF
Base frequency=50 Hz
Base speed=1500 rpm

- Air gap voltage

The piecewise linearization of magnetization characteristics of machine-1gives

$$X_m < 51.2 \quad E_1 = 277.53 - 1.42\, X_m$$

$$83.8 > X_m \geq 51.2 \quad E_1 = 328.7 - 2.42\, X_m$$

$$95.2 > X_m \geq 83.8 \quad E_1 = 349.44 - 2.67\, X_m$$

$$161.2 > X_m \geq 95.2 \quad E_1 = 116.144 - 0.22\, X_m$$

$$X_m \geq 161.2 \quad E_1 = 0$$

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