DESIGN OF A MECHANICAL-ELECTRICAL CONTROL SYSTEM FOR 100 kW WIND ELECTRICAL POWER GENERATION PLANT USING A 3-PHASE SQUIRREL CAGE INDUCTION GENERATOR

PERANCANGAN SISTEM KONTROL MEKANIS-ELEKTRIS UNTUK PEMBANGKIT LISTRIK TENAGA BAYU 100 kW MENGGUNAKAN GENERATOR INDUKSI 3 FASA TIPE SANGKAR

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Received: 23 May 2009, Accepted for publication: 13 September 2009

ABSTRACT
To support the realization of energy mix 2025 an initiative was launched in the beginning of 2009 by the Research and Development Center for Electricity Technology and New/Renewable Energy in cooperation with the Research Center for Electrical Power and Mechatronics to build a 100 kW wind electrical power generation plant using as much national capabilities as possible. This paper addresses the design of a mechanical-electrical control system for the power plant. The mechanical control system consists of mechanical brake and yaw control while the electrical control system consists of electrical power control. To optimize energy conversion a new method is proposed. A supervisory controller is designed to maximize wind turbine power coefficient while a local controller is designed to control the generator rotational speed. From the computer simulation with duration of 8 sec carried out in this paper, it was obtained that the power control scheme with constant speed at 22.39 rpm captured energy of 153.7 joule, with constant speed at 36.7 rpm captured 177.6 joule, and the power control scheme with variable rotational speed captured wind energy of 200.9 joule.

Keywords: mechanical-electrical, control, 100 kW, wind, electrical power, induction generator

INTISARI

Kata kunci: mekanis-elektis, kontrol, 100 kW, bayu, daya listrik, generator induksi

1. INTRODUCTION
Measurement of wind speed and direction at a selected location at west coast of Java has been conducted for one year. Figure 1 shows histogram of the measured wind speed [1]. The anemometer set at 30 meter height measured the wind speed at interval of 190 minutes in one year long.

The National Institute of Aeronautics and Space (LAPAN) has been conducting research on wind electrical power generation [2]. To support
realization of national energy mix target, as described in the energy white book, an initiative has been launched in 2009 to build 100 kW wind electrical power generation by the Research and Development Center for Electricity Technology and New/Renewable Energy in cooperation with the Research Center for Electrical Power and Mechatronics.

A wind turbine converts wind kinetics energy to turbine kinetics energy according to the following rule.

\[ P_{\text{ai}} - P_{\text{ao}} = P_m + P_p + P_l \]  

(1)

The difference between wind power entering to the turbine \( P_{\text{ai}} \) (Watt) and the wind power leaving the turbine \( P_{\text{ao}} \) equals to the sum of turbine kinetics power \( P_m \), mechanical structure potential power \( P_p \) and power loss converted to other form of power \( P_l \). In the case of an ideal horizontal turbine with assumption that the free wind has constant speed, is homogeneous and uncompressible, and flows laminarily, theoretically the net wind power \( P_w \) (difference between output–input wind power) is given by the following equation:

\[ P_w = \left( \frac{16}{27} \right) \frac{1}{2} \rho A v^3 \]  

(2)

\( \rho, A \) and \( v \) denote air density, swept area of the turbine rotor and free flowing wind speed, respectively. The coefficient \( \left( \frac{16}{27} \right) \) is the maximal power coefficient for an ideal horizontal wind turbine derived by Betz.

Many researchers have been conducted on control of wind turbine electrical power generation plants, however most of papers reported variable speed control approach using blade pitch control. This paper addresses a conceptual design of mechanical-electrical control system for 100 kW wind electrical power generation plant using 3 phase induction generator. Firstly, wind turbine performance is reviewed. Secondly, 3 phase induction generator model is described. Third, conceptual design of mechanical-electrical control system is proposed to suit to the 100 kW wind electrical power generation plant. Mechanical control consists of dynamical control of mechanical brake and yaw. Electrical control is devoted to optimize power absorption by variable speed operation. Finally, conclusion and recommendation is given.

2. WIND TURBINE

Figure 2 shows the illustration of horizontal wind turbine which will be built in this research activity. This wind turbine has capacity of 100 kW with height of the hub 35 m and the rotor diameter of 24 m.

In the real world, wind power that can be converted to turbine kinetics power is given by

\[ P_m = C_p \left( \frac{1}{2} \rho A v^3 \right) \]  

(3)

The value of power coefficient \( C_p \) depends on turbine blade construction, its aerodynamics parameter and wind speed and direction.

Figure 1. Wind speed measurement result

Figure 2. Horizontal wind turbine 100 kW
Mechanically, a wind turbine performance can be evaluated by its power coefficient under mechanical constrains including structural strength and fatigue. Its performance and constrain are function of aerodynamics torques. Figure 3 shows aerodynamics of turbine blade where the developed force is eventually broken down into tangential force $F_t$ and axial force $F_a$.

When the rotor rotates with rotational speed $\omega_p$ perpendicular to the wind direction which flows with speed $v_r$ it sees relative wind speed $v$. The aerofoil experiences lift force $F_l$ which rotates the blade rotor and drag force $F_d$ which puts mechanical load to the wind turbine structure. The lift force and drag force can be expressed in the following equation.

\[ F_l = C_L \frac{1}{2} \rho A v^2 \]  \hspace{1cm} (4)

\[ F_d = C_D \frac{1}{2} \rho A v^2 \]  \hspace{1cm} (5)

A wind turbine performance can be evaluated by observing 3 keys performance indicator i.e. kinetics power $P_m$, tangential torque $T_t$ and axial torque $T_a$ in relation with wind speed. Generally, the performance is expressed as a function of tip speed ratio (TSR) $\lambda$ where $\lambda = \frac{R\omega_p}{v}$. $R$ expresses the radius of the blade tip to the hub center. Figure 4 shows relationship between wind turbine performance (kinetic power coefficient $C_p$, tangential torque coefficient $C_t$ and axial torque coefficient $C_a$) and tip speed ratio $\lambda$.

Solid line with asterisks shows power coefficient, broken line with squares demonstrates tangential torque coefficient, and the dotted line with diamonds indicates axial torque coefficient. In high tip speed ratio regime the power coefficient declines because of drag power loss. In this regime much wind power is absorbed and converted to potential/internal power of the mechanical structure. Conversely, in low tip speed ratio regime, power coefficient declines because of stall power yielding mechanical structural vibration. Tangential torque determines transmission gear specification and mechanical brake specification while axial torque determines tower structural specification.

Figure 5 shows effect of rotational speed of wind turbine on the kinematics power absorbed by the wind turbine. It is obvious that for low wind speed the lower turbine rotor speed is the better. Oppositely, for high wind speed the higher turbine rotor speed is more preferable. This fact argues a variable rotor speed control to maximize wind power conversion to electrical power.

Figure 3. Blade aerodynamics

Figure 4. Wind turbine performance

Figure 5. Power vs. speed of a wind turbine
3. INDUCTION GENERATOR

A 3 phase induction generator generates electrical power by converting mechanical energy provided by the turbine by the help of induced magnetic field. An induction generator is made up of two major components: (1) the stator which consists of steel laminations mounted on a frame so that slots are formed on the inside diameter of the assembly, and (2) the rotor which consists of a structural of steel laminations mounted on a shaft with two possible configurations: wound rotor or cage rotor. Wound rotors are usually available for very large power machines (>500 kW). External converters in the rotor circuit, rated with slip power, control the secondary currents providing the rated frequency at the stator. For most medium power applications squirrel cage rotors are used. Squirrel cage rotor windings consists of solid bars of conducting material embedded in the rotor slots and shorted at the two ends by conducting rings. Rotors are usually stacked in a mold made by aluminum casting enabling an economical structure combining the rotor bars, rings, and fan[7].

Given base value or rated value of angular frequency \( \omega_b = 2\pi f_{rated} \) (electrical radians per second), voltage equations of a 3 phases symmetrical induction machine in terms of flux linkage per second \( \psi' \) (\( \omega_b \lambda \) volt or per unit) and reactance \( x = \omega_b L \) (Ohm or per unit) in a synchronously rotating reference frame \( qd0 \) are given below[6].

\[
\begin{align*}
V_{qs} &= r_s i_{qs} + \frac{1}{\omega_b} \frac{d\psi'_{qs}}{dt} + \frac{\omega_e}{\omega_b} \psi'_{dqs} \\
V_{qs} &= r_s i_{qs} + \frac{1}{\omega_b} \frac{d\psi'_{qs}}{dt} - \frac{\omega_e}{\omega_b} \psi'_{dqs} \\
V_{0s} &= r_s i_{0s} + \frac{1}{\omega_b} \frac{d\psi'_{0s}}{dt} \\
V_{qr} &= r_s i_{qr} + \frac{1}{\omega_b} \frac{d\psi'_{qr}}{dt} + \frac{\omega_e - \omega_r}{\omega_b} \psi'_{dqr} \\
V_{dr} &= r_s i_{dr} + \frac{1}{\omega_b} \frac{d\psi'_{dr}}{dt} - \frac{\omega_e - \omega_r}{\omega_b} \psi'_{dqr} \\
V_{0r} &= r_s i_{0r} + \frac{1}{\omega_b} \frac{d\psi'_{0r}}{dt} 
\end{align*}
\]

The variables \( v, i \) and \( r \) denote voltage, current and resistance respectively. The subscripts \( q, d \) and \( 0 \) represent that the variable is on the \( q \) axis, \( d \) axis and \( 0 \) axis. The subscripts \( s \) and \( r \) indicate that the variable belongs to the stator circuit and the rotor circuit, respectively. The superscript \( e \) indicates that the variable is expressed in the synchronously rotating reference frame \( qd0 \). \( \omega_e \) denotes the speed of the synchronously rotating reference frame \( qd0 \) which equals to the angular speed of the stator magneto motive force in electrical radians per sec, while \( \omega_r \) denotes the speed of the rotating rotor magneto motive force. The primed \( ' \) rotor quantities denote values are referred to the stator side.

The flux linkage equations are given as follows.

\[
\begin{align*}
\psi_{qs} &= (x_{ls} + x_m) i_{qs} + x_m i_{gr} \\
\psi_{qs} &= (x_{ls} + x_m) i_{ds} + x_m i_{dr} \\
\psi_{0s} &= x_{ls} i_{0s} \\
\psi_{qr} &= x_m i_{qr} + (x_{ds} + x_m) i_{dr} \\
\psi_{dr} &= x_m i_{dr} + (x_{ds} + x_m) i_{qr} \\
\psi_{0r} &= x_{dr} i_{0r}
\end{align*}
\]

\( x_q \) represents the stator winding leakage reactance, \( x_m \) the magnetizing reactance on the stator side, and \( x_r \) the rotor winding leakage reactance on the stator side.

The electromechanical torque developed by the machine \( T_{em} \) (Nm) is given by the following equation.

\[
T_{em} = \frac{3}{2} \frac{P}{2\omega_b} \left( \psi_{qr} i_{dr} - \psi_{dr} i_{qr} \right)
\]

\( P \) denotes the number of magnetic poles.

For steady-state operation of the induction machine with a balanced three-phase sinusoidal voltages and currents, with assumption that the machine is operated at constant voltage rms time phasor of the stator winding and with the terminal of the rotor windings be shorted, the average value of the power converted from the mechanical work \( P_{mec} \) (\( = P_{converted} \)) is given as follows.

\[
P_{mec} = \frac{3V_{th}^2}{2} \frac{\left( \frac{\omega_e}{\omega_b} \right) (1 - s)}{\left( \frac{\omega_e}{\omega_b} + \frac{\omega_r}{\omega_b} \right)^2 + (x_m + x_r)^2}
\]
The quantities $V_{th}$, $r_h$ and $x_h$ represent voltage, resistance and reactance of the Thevenin's equivalent circuit of the induction machine. $s$ denotes the normalized slip speed also referred to simply as the slip.

$$s = \frac{\omega_{sm} - \omega_{rm}}{\omega_{sm}} = \frac{\omega_e - \omega_r}{\omega_e}$$  \hspace{1cm} (11)

$\omega_{sm}$ is synchronous speed in the mechanical radians per sec while $\omega_{rm}$ is the rotor rotating speed in mechanical radians per sec. Slip $s$ is negative in generating operation when the rotor rotates above synchronous speed.

The electromagnetic torque developed by the induction machine is the mechanical (=converted) power divided by the rotor mechanical speed $\omega_{rm}$.

$$T_{em} = \frac{P_{mec}}{\omega_{rm}} = \frac{P_{mec}}{\omega_{sm}(1-s)} = \frac{p}{2\omega_e(1-s)} \left( \frac{V_s^2}{\frac{r_h}{2} + \frac{x_s}{2}} \right) \left( x_h + x_e \right)$$  \hspace{1cm} (12)

Figure 6 shows steady state characteristics pattern (power and torque) of a 3 phase induction machine calculated from equations (10) and (12).

The induction machine works as an ac motor in the positive slip domain and as a generator in the negative slip domain. The solid line expresses mechanical power while the broken line expresses electro mechanical torque. When mechanical power supplied by the turbine varies the generator slip varies accordingly. Mechanical power or electro mechanical torque of an induction generator can be controlled by controlling the generator slip.

4. DESIGN OF CONTROL SYSTEM

4.1. OVERALL CONTROLLER

In this paper a control system for wind turbine electrical power generations shown in figure 7 is proposed. In this figure, the plant to be controlled is represented by induction generator electrical model (IGEM), rotor motion equation, and wind turbine performance model (TPM). The overall mechanical-electrical controller is composed by mechanical brake controller (MBC), yaw controller (YC), pulse width modulator (PWM), local controller (LC), and supervisory controller (SC). Using appropriate sensors, the supervisory controller reads wind speed $v_w$, rotor mechanical rotational speed $\omega_{rm}$, rotor mechanical rotational position $\theta_{rm}$, yaw rotational position $\theta_y$, voltage $v_{ge}$, and current $i_{ge}$. The supervisory controller creates and sends yaw rotational position reference signal $\theta_y^*$ to the yaw controller and mechanical brake torque reference signal $T_b^*$ to the mechanical brake controller. Simultaneously, the supervisory controller also creates and sends rotor electrical rotational speed reference signal $\omega_e^*$ and stator electrical rotational speed reference signal $\theta_e^*$ to the local controller.

![Figure 6. Steady state characteristics](image-url)
The supervisory controller in this paper uses the following formulas to generate rotor speed reference signal and stator speed reference signal.

\[
\omega_r^* = \frac{\lambda_{opt}}{R} v_v
\]  
(13)

\[
\omega_s^* = \frac{\omega_r^*}{1 - s_{opt}}
\]  
(14)

Where \( \lambda_{opt} \) and \( s_{opt} \) denote optimal tip speed ratio and optimal slip, respectively.

4.2 MECHANICAL CONTROLLER

The mechanical controller in this paper is composed by a mechanical brake controller (MBC) and a yaw controller (YC). Due to space limitation only torque specification derivation is described in this paper. Motion equation of the wind turbine generator at High Speed Shaft (HSS) is given by

\[
J_{HSS} \ddot{\theta}_{HSS} + D \dot{\theta}_{HSS} = T_m - T_{em} - T_B
\]  
(15)

where \( J_{HSS} \) is the moment of inertia at HSS (280 kg.m\(^2\)) and \( \theta_{HSS} \) is its rotational speed.

The brake torque is calculated according to the following procedure:

1) Assuming the wind electrical generation plant is operating at maximum rated power and maximum rated rotational speed \( \omega_i \).

2) The brake controller suddenly realizes 10% over speed after a grid loss and then starts recording time. After having passed \( \Delta t \) second the rotational speed further increases to become \( \omega_2 \) at which the brake is started to be engaged.

3) The wind turbine stops rotating at interval time of \( \Delta t_B \).

To realize the above braking procedure the following formulae has been derived.

\[
T_B = J_{HSS} \left\{ \frac{\omega_2 - 1.1 \omega_i}{\Delta t} + \frac{\omega_2}{\Delta t_B} \right\}
\]  
(16)

Yaw moments on rigid hub machines arise from differential loading on the blades. According to the investigation of three-blades wind turbines conducted by Anderson et al (1993) it is known that the major source of the cyclic yaw loading is stochastic at 3P while yaw error was not found to make a significant contribution[9]. Assuming a
three blades wind turbine is rotating at rotational speed of \( \omega \), by taking into consideration the first four harmonics, the yaw moment from all three blades is given by

\[
M_{zt} = \frac{3}{2} \left( a_1 \cos \phi - a_1 \cos(3\omega t + \phi_1) + a_1 \cos(3\omega t + \phi_2) + a_4 \cos(3\omega t + \phi_4) \right)
\]

(17)

The blade out-of-plane bending harmonics at 2P (associated by \( a_1 \)) and 4P (associated by \( a_4 \)) produce yaw moment at 3P (associated by \( 3\omega \)), while those at 1P (associated by \( a_1 \)) and 3P (associated by \( a_2 \)) produce steady \( a_1 \cos \phi_1 \) and zero \( a_3 = 0 \) yaw moments respectively. The main sources of blade out-of-plane loading at 2P are tower shadow and turbulence.

A yaw drive mechanism in this paper is designed in order to bear the above yaw moments due to the out-of-plane bending harmonics as well as to track the wind turbine to be always perpendicular to the wind direction. Thus the yaw drive should satisfy the following torque specification.

\[
T_{yd} \geq [M_{zt} + T_{rr}]_{max}
\]

(18)

The yaw drive torque capacity \( T_{yd} \) is equal to or more than the possible maximum value of the sum of the bending harmonics torque \( T_{zt} \) and yaw tracking torque \( T_{rr} \).

4.3. ELECTRICAL CONTROLLER

In this paper, a generator torque controller is designed using field oriented control approach[10]. When the synchronously rotating reference frame \( dq0 \) is selected so that its \( d \)-axis is aligned with the rotor field, the \( q \)-component of the rotor field \( \lambda_{dq}^e \) in the chosen reference frame would be zero. As a result, from the flux linkages equations in (8) and from the torque equation in (9) the following equations are obtained.

\[
i_{qr}^e = -\frac{L_m}{L_r} i_{qr}^e \quad \text{(A)}
\]

(19)

\[
T_{em} = \frac{3}{2} \frac{p}{2} \frac{L_m}{L_r} \lambda_{qr}^e i_{qr}^e \quad \text{(Nm)}
\]

(20)

Substituting (20) into (19) yields

\[
T_{em} = \frac{3}{2} \frac{p}{2} \frac{L_m}{L_r} \lambda_{dr}^e i_{qr}^e \quad \text{(Nm)}
\]

(21)

This shows that if the rotor flux linkage \( \lambda_{dr}^e \) is not disturbed, the torque can be controlled by the stator \( q \)-component current \( i_{qr}^e \).

Another consequence of the assumption that the \( q \)-component of the rotor field be zero (\( \lambda_{qr}^e = 0 \)) and by recalling that the rotor voltages are zero can be derived by substituting \( \frac{d\lambda_{qr}^e}{dt} = 0 \) and \( v_{qr} = 0 \) into \( q \)-axis voltage equation of the rotor winding in equation (7) to get the following relationship.

\[
\omega_e - \omega_r = \frac{1}{j_{sr}} \frac{v_{qr}^e}{L_r} \quad \text{E lect. rad./sec}
\]

(22)

On the other hand if the rotor flux linkage in \( d \)-axis is not disturbed \( \frac{d\lambda_{dr}^e}{dt} = 0 \) and by recalling the \( q \)-component of the rotor field be zero in the \( d \)-axis (\( \lambda_{qr}^e = 0 \)), from the \( d \)-axis rotor voltage equation in (7) the following is obtained.

\[
\lambda_{dr}^e = L_m i_{dr}^e
\]

(23)

Substituting (23) and (19) into (22) the following can be derived.

\[
\omega_e - \omega_r = \frac{v_{dr}^e}{L_r} \frac{L_m}{j_{sr}} i_{dr}^e
\]

(24)

From \( d \)-component rotor flux linkage equation it clear that \( i_{dr}^e = \frac{1}{L_r} \left( \lambda_{dr}^e - L_m i_{dr}^e \right) \). Substituting this into \( q \)-axis rotor voltage equation yields

\[
L_r \frac{d\lambda_{dr}^e}{dt} + r_p \lambda_{dr}^e = r_p L_m i_{dq}^e
\]

(25)

Introducing Laplace transform variable \( s_L \) the above equation reduces to

\[
\lambda_{dr}^e = \frac{L_m}{1 + \tau s_L} i_{dr}^e
\]

(26)

where \( \tau = \frac{L_r}{r_p} \) is the rotor circuit time constant.

Given a desired value of rotor flux \( \lambda_{dr}^e \) the desired value of \( i_{dr}^e \) can be calculated using equation (26). On the other hand, given a desired value
of torque $T_{em}^*$ at the given value of rotor flux, the desired value of $i_{em}^*$ can be obtained. The rotor field orientation angle $\sigma$ is estimated using the following equation.

$$\sigma = \omega_e - \omega_d dt + \theta_e$$

$$= \frac{r_e}{L_r} \int \left( i_{d}^{*} \right) dt + \theta_e$$  \hspace{1cm} (27)

The rotor angle $\theta_e$ is measured using a rotor rotational position sensor. Figure 8 shows the block diagram of the generator rotor speed tracking control using the field orientation control approach described above.

5. SIMULATION RESULTS

Figure 9 shows the generator characteristics as a function of slip with constant electrical speed of 50 Hz. This generator has rated power of 150 kW, rated voltage of 380V, and speed of 1500 rpm.

In the upper figure, the solid line shows mechanical power from the turbine while the dotted line shows the electromagnetic power transferred from rotor to stator through air gap. The broken line is electromagnetic torque developed between rotor and stator.

In generating mode the air gap power is smaller than the mechanical power because of rotor core loss. In the lower figure, the solid line shows electrical active power while the broken line shows electrical reactive power at the stator.

Taking into account the wind speed measurement result shown in figure 1, for simulation purpose in this paper wind speed pattern shown in figure 10 is used. During simulation it is assumed that the mechanical brake does not need to be operated and that the yaw control can performs well so that the wind turbine direction is always perpendicular to the wind incoming direction.

Figure 11 shows simulation results when the wind speed pattern is applied to the wind turbine with the wind turbine rotational speed is kept constant at 22.39 rpm. The upper figure shows the rotational speed of the induction generator rotor.

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**Figure 8.** Generator rotor speed tracking control using field oriented control approach

**Figure 9.** Generator power characteristics

**Figure 10.** Wind speed pattern in simulation
(HSS / high speed shaft) which is equals to the rotational speed of the wind turbine rotor (LSS / low speed shaft) multiplied by the gear ratio. It can be observed that the control system gives good performance in regulating the rotational speed. Whenever the rotational speed is disturbed by wind speed change, it is regulated back to the set point.

The lower figure in figure 11 shows power histories. The dotted line is the mechanical power delivered by the turbine to the generator while the solid line is the electro-mechanical power generated in the generator rotor. The total energy delivered by the wind turbine is 153.7 joule. It is obvious that the control system is capable to regulate rotational speed as well as to track wind turbine mechanical power.

Figure 12 shows the simulation results when the wind speed pattern is applied to the wind turbine where the generator rotor speed is controlled to be constant at 36.67 rpm. The total energy delivered by the wind turbine is 177.6 joule. Again, it is obvious that the control system is capable to regulate rotational speed as well as to track wind turbine mechanical power.

By observing power histories in figure 11 and figure 12 it can be realized that not all wind power is captured by the wind turbine. Power control with constant speed at 22.39 rpm can only capture wind energy at low wind speed domain. Oppositely, power control with constant speed at 36.7 rpm can only capture wind energy at medium wind speed domain while loosing wind energy at both low wind speed and high wind speed.

Figure 13 shows simulation results when the wind speed pattern is applied to the wind turbine where the generator rotor speed is controlled in variable speed manner. The total energy delivered by the wind turbine is 200.9 joule. From the upper figure it can be seen that the rotational speed of HSS varies with time. From the lower figure it is clear that the power control system can capture wind energy at low, medium and high wind speed domain.

6. CONCLUSION

From simulation results in this paper the following conclusion can be drawn:

1. The dynamical models of wind turbine and induction machine, with specification of 150 kW 380 V 1500 rpm, developed in this paper have been integrated to simulate a wind turbine electrical power plant.
2. The electrical torque/power controller together with the power supervisory controller designed in this paper can function well in the computer simulation.

3. From the simulation with duration of 8 sec carried out in this paper, it was obtained that the power control scheme with constant rotational speed at 22.39 rpm captured wind energy of 153.7 joule, the power control scheme with constant rotational speed at 36.7 rpm captured wind energy of 177.6 joule, and the power control scheme with variable rotational speed captured wind energy of 200.9 joule.

7. REFERENCES


