# Cooperation of induction squirrel-cage generator with grid connected AC/DC/AC converter

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**Abstract.** The paper presents a squirrel-cage induction machine operating as a generator principally designed for use in small wind and hydroelectric power stations. The main advantages of such a generator are its high reliability, low price and costs of operation and maintenance. The asynchronous generator coupled to the grid through the AC/DC/AC converter is capable of generating energy even at low turbine speed. The results of investigations on the AC/DC and DC/AC converters controlled by linear and nonlinear current regulators are also discussed.

**Key words:** asynchronous generator, AC/DC/AC converter, PWM method of control, nonlinear method of control.

## 1. Introduction

Both wind and water energy can be converted into electrical energy in various electromechanical systems using induction and synchronous generators with separate excitation and permanent magnets [1–5]. In electric power stations mainly double-fed induction generators are used. They constitute almost 50% of the installed power of the wind power plants in operation [1]. Part of them are induction machines working at fixed turbine speed [6–7]. The systems are characterized by a small range of speed changes at the time when energy is sent to the grid. In a historical perspective, to make a better use of various wind power: mechanical, electromechanical and electrical changes have been introduced. The improvements involved using constant and variable speed transmission mechanisms, variable pitch angle of turbine blades, changeable number of pole pairs as well as wound-rotor motors with controlled resistance and power electronic converters used practically in all modern systems. A list of conditions that should be fulfilled by a system used to produce electrical energy from wind power is given below.

- The generator should be adapted to operate at variable angular turbine velocity at the largest possible range to make maximum use of weak winds.
- The generator should provide efficient conversion of wind power into electrical energy (high efficiency of the whole system).
- The energy sent to the grid should be characterized by a low levels of higher harmonics.
- The generator design should take extreme working conditions and emergency situations into consideration. It should have suitable braking systems protecting it against strong gusts of wind and other dangers that may occur in this type of systems.
- The actual construction of the generator should ensure long-lasting, failure-free and low-noise operation. Addi-

tionally, its design should enable easy, quick and infrequent maintenance or repairs.
- The generators should be relatively light and small in size but, first of all, inexpensive to buy and also cheap to operate.

The above requirements are fulfilled by three types of wind power plants additionally equipped with power electronic converters [8–12]:

- wind power plant with squirrel-cage asynchronous generator (SCAG),
- wind power plant with double-fed asynchronous generator (DFAG),
- wind power plant with synchronous generator (SG) and separate excitation or permanent magnets.

With respect to their technical specifications all the above types possess similar characteristics – their main advantage lying in the possibility of producing electrical energy even at very low shaft angular velocity. Efficiency of energy conversion depends on both mechanical and electrical factors. Assuming that the mechanical efficiency of a device (i.e. its turbine and the transmission system) have the same efficiency, then the device's efficiency will be dependent on its electrical properties (i.e. motor and converter efficiency). Machines are characterized by similar efficiency, however, a double-fed induction machine shows the lowest efficiency between them due to the way in which the energy is transferred through its stator and rotor. The key element in the efficiency chain is the power electronic converter. In theory, all the converters possess similar efficiency but in the case of the converter co-operating with a double-fed induction generator, only part of the energy is converted inside it, which should make the conversion method work with higher efficiency. In the remaining two methods the converter transforms the whole energy produced by the generator. The final effect of an investment depends on satisfying all the necessary technical

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requirements ensuring appropriate working and safety standards. In turn, the economic results are determined by the costs of the investment, operation and efficiency of energy conversion. Comparing the investment costs outlays, or actual cost differences, one can state that the synchronous generator is the most costly, whereas the asynchronous one is the least expensive. Also the operation and maintenance costs are the lowest for the latter. The greatest fallibility characterizes the machines equipped with slip rings i.e. double-fed induction machine and synchronous machine with external excitation. DFAG system requires a lower power converter than in the other two systems and hence, it is the cheapest one [13]. Efficiency of the converter plays the key role in the overall output of the generator, especially in SCAG and SG systems in which the whole energy is converted. The converter efficiency is directly determined by the average switching frequency of power electronic devices, i.e. the control method. As regards to the generator, some current distortion is acceptable, unlike in the grid converter in which current and voltage distortions cannot be accepted. Considering their effectiveness, non-linear control methods could be more advantageous because of lower switching frequency with similar properties of output such as torque and current ripples. In the case of the grid converter, linear current controllers seem to be more suitable since, at constant frequency modulation, it is easier to design the output current filter [14]. In the presented paper we analyse a turbine coupled with an asynchronous squirrel cage generator.

## 2. Concept of converter control

The way in which the generator controls system is built depends on its function in the electric power system. It may be working as one of many others on a wind turbines farm, as a single generator connected to the grid and also as a generator working "on island" [15] or as uninterruptible power supply (UPS). The power of the turbine at wind's constant speed $v_w$, assumes a shape characterized by a clearly visible power maximum that can be utilized (Fig. 1) [2, 16–18]. The maximum value, depending on the wind speed, occurs at different values of the turbine shaft speed. To make an optimal use of the turbine's work, it is necessary to utilize its power in the way shown by the dotted line. The turbine characteristics may be additionally determined by the turbine construction, i.e. the turbine motion and changes of its blade pitch angle.

In this paper, it is assumed that the turbine works as a single generator connected to the grid. At low turbine's power, it can be assumed that the turbine, at any given shaft speed, works with its maximum power to make optimal use of it. Thus, no limits are imposed on the maximum power that can be sent to the grid. The turbine is coupled to the generator's shaft using a constant ratio gear resulting from the relation between synchronous generator speed and the maximum allowable turbine speed. The idea of converter control which makes it possible to perform the described above task

is shown in Fig. 2 [19]. The DC/AC converter connects the generator windings to the DC link represented by capacitor C.
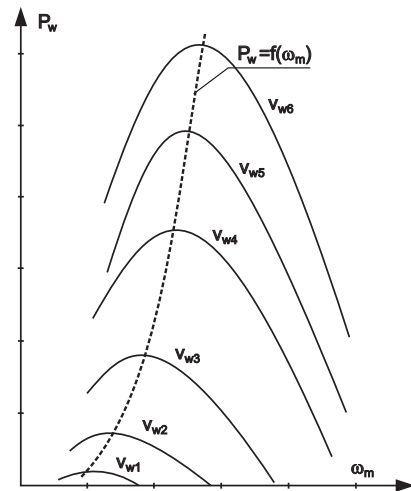


Fig. 1. Characteristics of wind turbine power as dependent on wind speed $v_w$
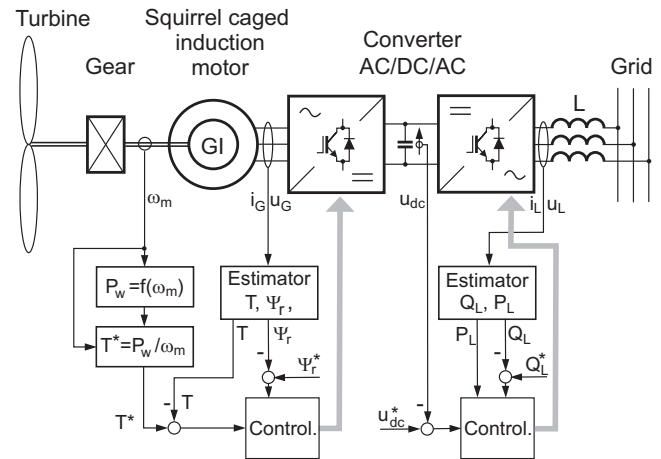


Fig. 2. Diagram of the AC/DC/AC converter control

In order to make a maximum use of wind and turbine power by using the relation $P_w = f(\omega_m)$ at a given angular speed of the shaft $\omega_m$, the power obtained from the turbine is determined. Next the set value of torque $T^*$ at witch the generator should be working is determined in order to attain maximum power at a given angular speed $\omega_m$. The AC/DC grid converter transfers the energy from the DC link to the three-phase grid. The converter is controlled by the main voltage control loop of the capacitor (DC link). The above loop is created for two reasons:

- to provide an appropriate voltage value to make it possible to shape the sinusoidal current transferred to the grid under fixed conditions (grid voltage value, current and inductance of grid choke) [20–21],
- to protect the converter against overvoltages that may occur due to the differences between the delivered and received energy from the DC link.

The internal control loop of the asynchronous generator is identical to the one used in the squirrel cage motor [22]. Figure 3 shows a system with direct field oriented control method (DFOC). Both flux and torque are controlled in two separated paths. The internal control circuits consist of controllers of current components $i_d$ and $i_q$ working in the rotating reference frame $dq$. The controllers of torque, rotor flux and current components are made as PI type linear controllers and its parameters are designed according to the rules that result from the module or symmetry criterion. Electromechanical state variable (flux, torque and speed) can be estimated using procedure described in references [23–25]. There are no specific requirements concerning the dynamics of the controlled quantities. The generator works at constant flux values and a transition to the second zone flux control (decrease of flux) is rarely used. Torque set value $T^*$ is variable, however the change rate of its value is limited by the change rates of the turbine angular speed $\omega_m$. Thus, the dynamics of the changes of the given power and torque is several orders of magnitude smaller than the time constants of torque control (several to several dozen of milliseconds) possible to achieve by using linear controllers. The reactive power (to magnetize the machine) circulates between generator and DC/AC inverter, whereas the active power is transmitted to the grid. Figure 4 presents a detailed diagram of the control of the converter connecting the generator with the grid.
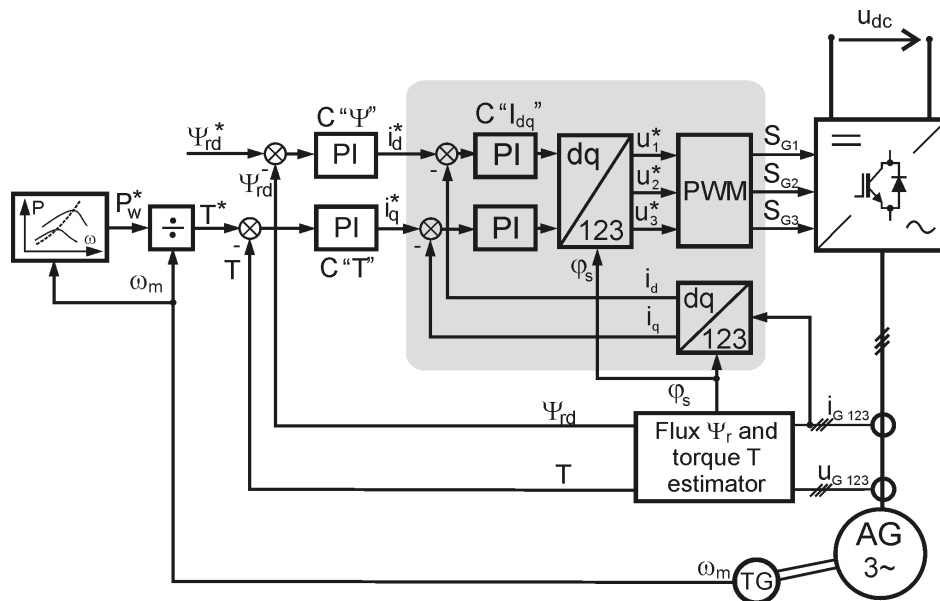

Fig. 3. DC/AC converter control of the squirrel cage generator
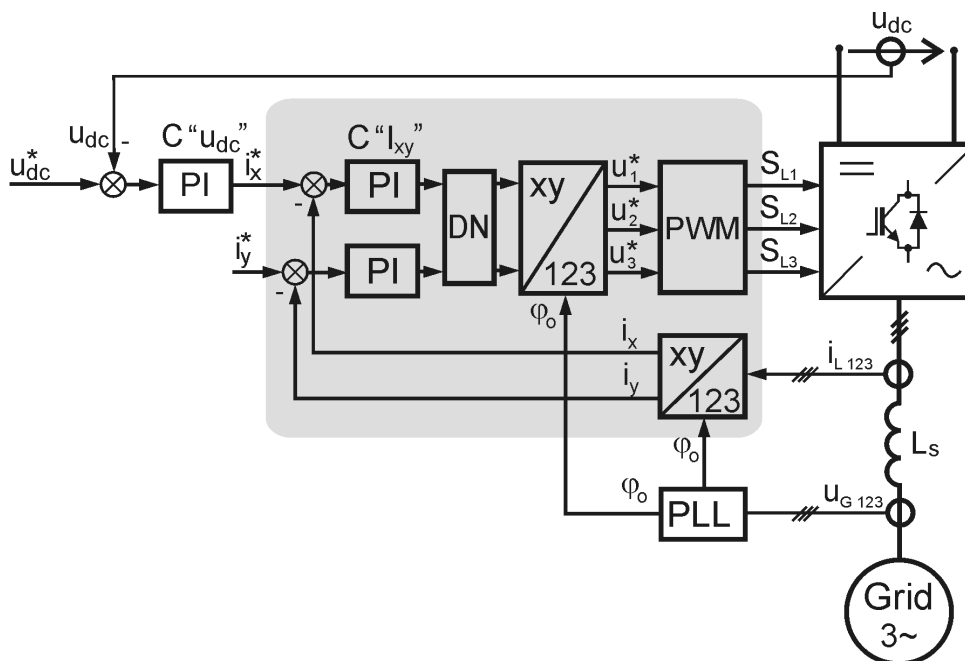

Fig. 4. AC/DC converter (grid converter) control of the squirrel cage generator system

The subordinate control systems were built using two-path current control loops working in rotating coordinate $xy$ (with grid angular frequency). The capacitor voltage error $(u_{dc}^* - u_{dc})$ determines the amplitude and direction of $i_x^*$ component directly proportional to the set value of the active power. The component $i_y$ is directly proportional to the reactive power generated into the grid. When a set current value $i_y^*$ equals to zero then the currents flowing into the grid remain in phase with the corresponding voltages in the supply grid – only active power is generated. The reference components $i_x^*$, $i_y^*$ are compared to the transferred to the rotating coordinates $xy$ the real currents $i_{L1}$, $i_{L2}$, $i_{L3}$. The output signals coming from PI current controllers, after passing the decoupling process (DN block), are transformed into the stationary $\alpha\beta$ coordinates and then into the three-phase system in the *xy/123* block. The angle $\varphi_O$, used for the operation of current vector rotation (transferring from $\alpha\beta$ into $xy$ coordinates and vice versa), is reproduced in phase locked loop (PLL). As for the DC/AC converter, high dynamics of current component controllers are not required here. Rapid changes of the current reference values can not takes place due to the type of the preceding PI controllers. A static accuracy is ensured by the controllers operating at quasi-constant values.

To compare the properties of the systems, investigations were carried out using non-linear comparator controllers of current [24]. A schematic diagram of such a regulator which was used instead of current controllers in Figs. 3 and 4 (shown against the gray background) is presented in Fig. 5. The type $\Delta$ controller has a very good dynamics [11].
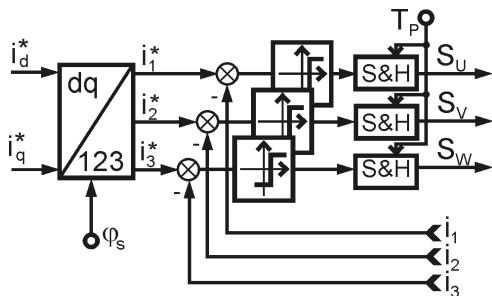
Fig. 5. Block diagram of type $\Delta$ current controller

## 3. Results of tests

The operation of AC/DC/AC current controllers employing the above algorithms was tested in the system co-operating with the induction machine (generator) driven by a DC motor (turbine simulator). The main data and parameters are given in Table 1.

Table 1
System parameters

| Generator | Grid |
|---|---|
| $P_N = 3.7$ kW | $U_{N(RMS)} = 200$ V |
| $U_N = 350$ V | $L = 30$ mH |
| $I_N = 10$ A | |
| $f_N = 51.6$ Hz | |
| $\omega_N = 324$ rad/s | |

The converter was controlled using dSPACE DS1103 board programmed in the Matlab Simulink 7.01 environment.

Figures 6 and 7 illustrate changes of voltage and phase current of both the generator and grid as well as the real torque $T$, rotor flux $\Psi_r$ and also active $P_L$ and reactive $Q_L$ powers returned to the grid when non-linear (Figs. 6a, 7a) and linear (Figs. 6b, 7b) current controllers are used. The sampling time $T_p$ of type $\Delta$ current controller and the frequency of PWM modulator (in linear controllers) were chosen in such a way as to be equal, in both cases, to the average switching frequency of the converter transistors (9.2 kHz in AC/DC and 8.2 kHz in DC/AC). Thus, it is possible to compare the converter properties such as accuracy of current, torque and power shaping (ripples), when the used converters have comparable efficiency [24].
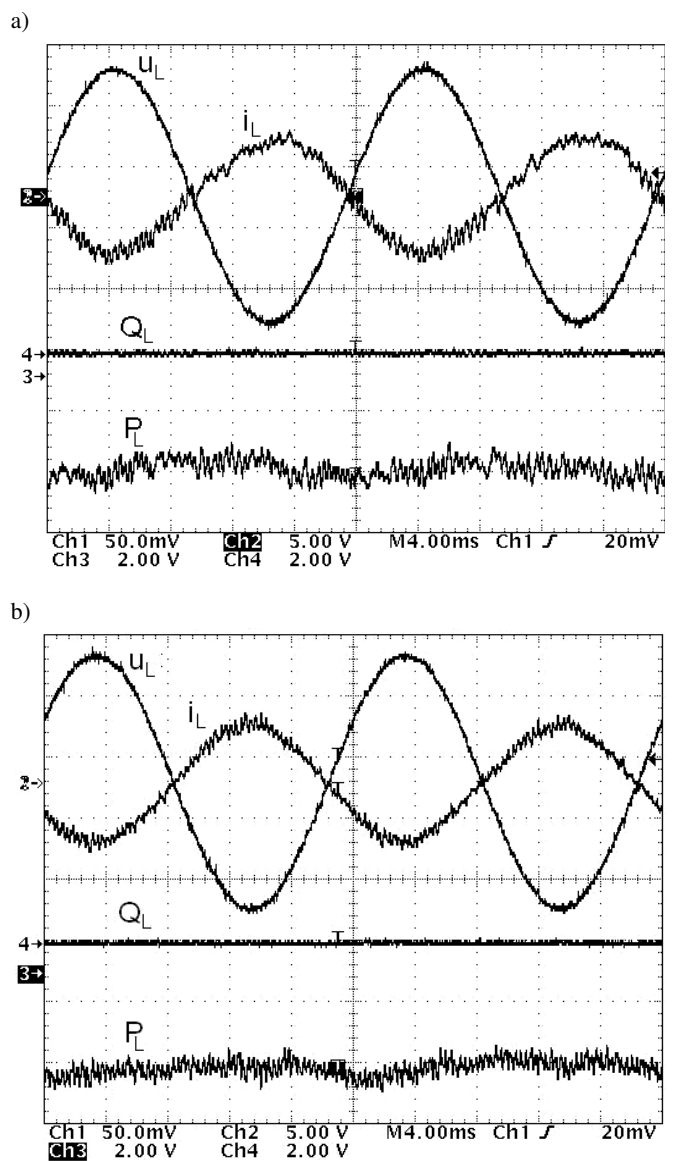
a)

b)

Fig. 6. Oscillograms of voltage $u_L$, grid current $i_L$ and active and reactive powers $P_L$ and $Q_L$ returned to the grid using non-linear (a) and linear (b) current controllers
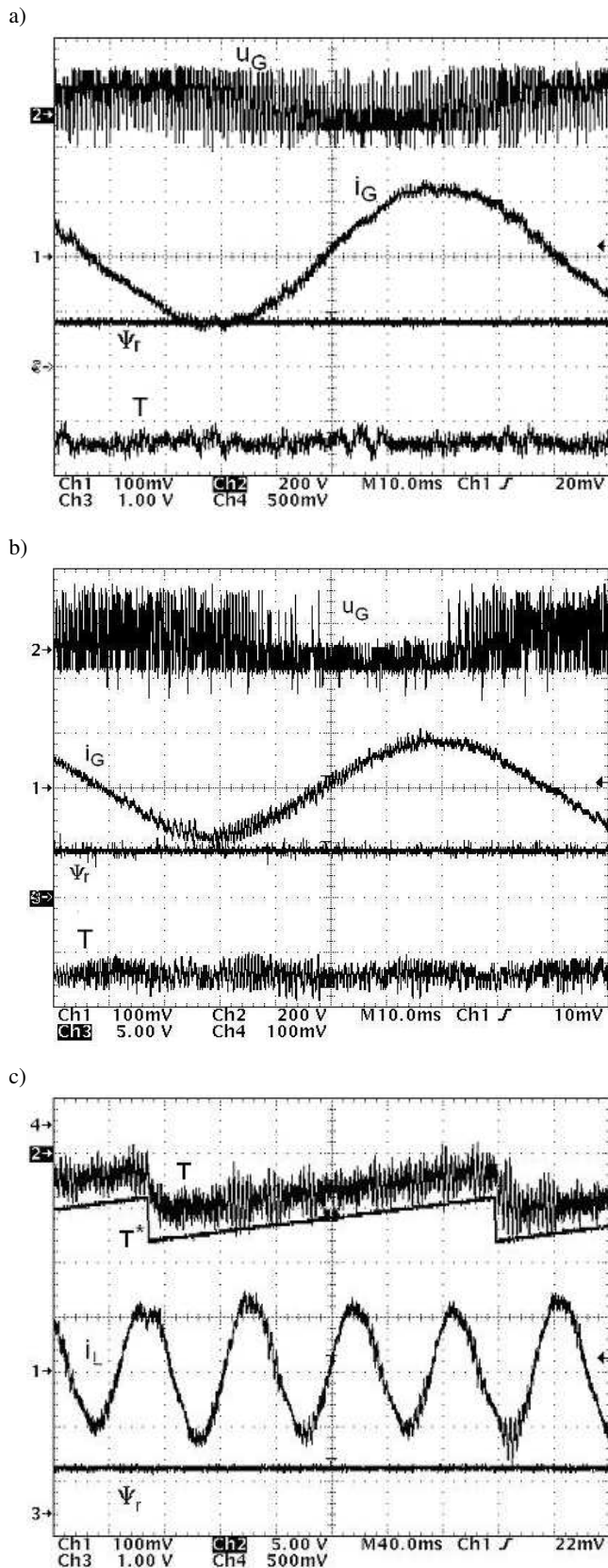
a)



b)



c)



Fig. 7. Oscillograms of voltage $u_G$, generator current $i_G$, rotor flux $\Psi_r$ and generator torque $T$ of the control system equipped with non-linear (a) and linear (b) current controllers and system response to both rapid and linear change of a reference torque $T^*$ (c)

The linear controller (in comparison to the non-linear $\Delta$ type) shows smaller current ripples, and as a result, smaller torque and power ripples in both converters (Figs. 6, 7, channel 1).

In the asynchronous generator, similarly to the DC generator, there is a possibility of controlling the output voltage(power) by controlling the rotor flux $\Psi_r$.

The AC/DC converter is controlled in such a way ($i_y^* = 0$) that the converter current (Fig. 6) remains in the opposite phase to the voltage so only active power ($Q_L = 0$) is returned to the grid.

## 4. Conclusions

A squirrel-cage generator may prove to be a very attractive solution for small wind and water power plants. Its main advantages include high reliability due to its simple construction requiring neither brushes nor commutators, low price comparable to other machines of the same power and low operating costs. The disadvantages of such a solution i.e. the necessity of generator excitation and problems connected with energy conversion at low drive speed, have been eliminated by use of the AC/DC/AC converter. The controlled, bidirectional AC/DC/AC converter makes it possible, for the reactive power, to flow from the grid to the generator for its excitation as well as send the active power from the generator to the grid (Fig. 7). Another very important advantage of the solution is a possibility of energy generation at a theoretically low angular speed of the turbine (when its power compensates both the generator and converter losses). In the tested system the speed was equal to 15 rad/s. The linear controller is characterized by lower current ripples in comparison with other controllers, especially if high dynamics is not an essential property for converters used in the considered system. Considering the minimization of switching frequency, predictive controllers seem to be the most appropriate solution [23]. However, their use requires a fast processor and, as a result, a relatively expensive equipment.

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