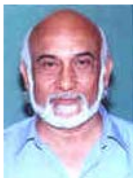
The Legacy of Nikola Tesla

2. AC Power System and its Growth in India

D P Sen Gupta

Electrical power supply has grown enormously during this century. In 1950 the total capacity of generators producing electricity in India was less than 3000 MW. Today, the power generating capacity is around 120,000 MW. The polyphase AC system, which is to a large extent the legacy of Nikola Tesla, is central to all power generation. Power systems these days are complex interconnected networks spread across the country. How are they structured? How have we been doing in India?



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Part 1. The Legacy of Nikola Tesla: The AC System that he helped to usher in, *Resonance*, Vol.12, No.3, pp.54–69, 2007.

Keywords
AC power system, Tesla, power situation in India.

1. Introduction

It was the end of the 19th century. Prospects of mining gold from Kolar in Mysore State was rich and the use of electricity would hold out the promise of digging into the depths of the mines. A source of hydroelectric power from Cauvery waters in Sivanasamudram had been identified, but considering those days, it was at a formidable distance of nearly 150 km! It was decided to make use of AC which had been slowly but surely winning the war against DC. But AC transmission over such a long distance would mean a large voltage drop! In DC transmission it is only the resistance that causes the voltage to drop and if the sending end voltage is V_s, the receiving end voltage is $V_r = V_s - IR$, where I is the current and R is the resistance of the conductor.

In the case of AC transmission in addition to resistance drop one also has to contend with voltage drop due to inductive reactance $X_L = 2\pi fL$, where L is the inductance of the transmission line and f is the frequency of supply. The total impedance to the flow of current is $Z = \sqrt{(R^2 + X_L^2)}$, where $X_L >> R$. (See *Box* 1 in Part 1). X_L can be kept low if f is low or L is low.

Long transmission lines cause large voltage drop mainly due to large inductance. In older days frequency was kept low in order to minimize voltage drop. The present practice is to reduce the effect of inductance by capacitive compensation.

It was decided to use lower value of frequency since the transmission line was the longest in the world at that time. In 1902, the first AC system in India was set up in Sivanasamudram to supply the Kolar gold mines. It generated 4.5 MW of power at 25 Hz and 33kV.

Much water has flown down the Cauvery since then and AC systems have completely displaced DC generation. The frequency of supply is 50 Hz all over the country. The generators in Sivanasamudram still generate power at 25 Hz, which is converted into 50 Hz and coupled to the main power system.

Now, the power generation in India has exceeded 120,000 MW. Long distances are now traversed at high voltage with means to compensate partially for reactive drops in voltage, if necessary.

India is now poised towards high growth and that may be possible only if we have a stable power system that promotes the burgeoning growth of the Indian economy. The per capita electrical energy consumption in India is still low and is less than 600 units/year compared to over 950 units in China and around 14000 units in USA. Nearly 65% of electrical energy in India comes from thermal sources, about 26.5% from hydroelectric sources, 3% from nuclear sources and about 2% from wind energy and the rest from other alternative sources. Our installed capacity for power production has to be increased significantly and losses in transmission and distribution reduced very significantly if we have to get out of the power crisis and stride ahead, having met the sad state of our rural power situation.

2. A Typical Power System

India's per capita electrical energy consumption is low at less than 600 units per year.

Figure 1 is a single line diagram of an AC system with its step-up and step-down transformers. It has to be realized, however, that AC generators are seldom operated in isolation. If the power requirement of a small town is 10 MW and we have a single generator of 10 MW supplying the load requirement of the town, we would need at least two 10 MW generators, one in operation

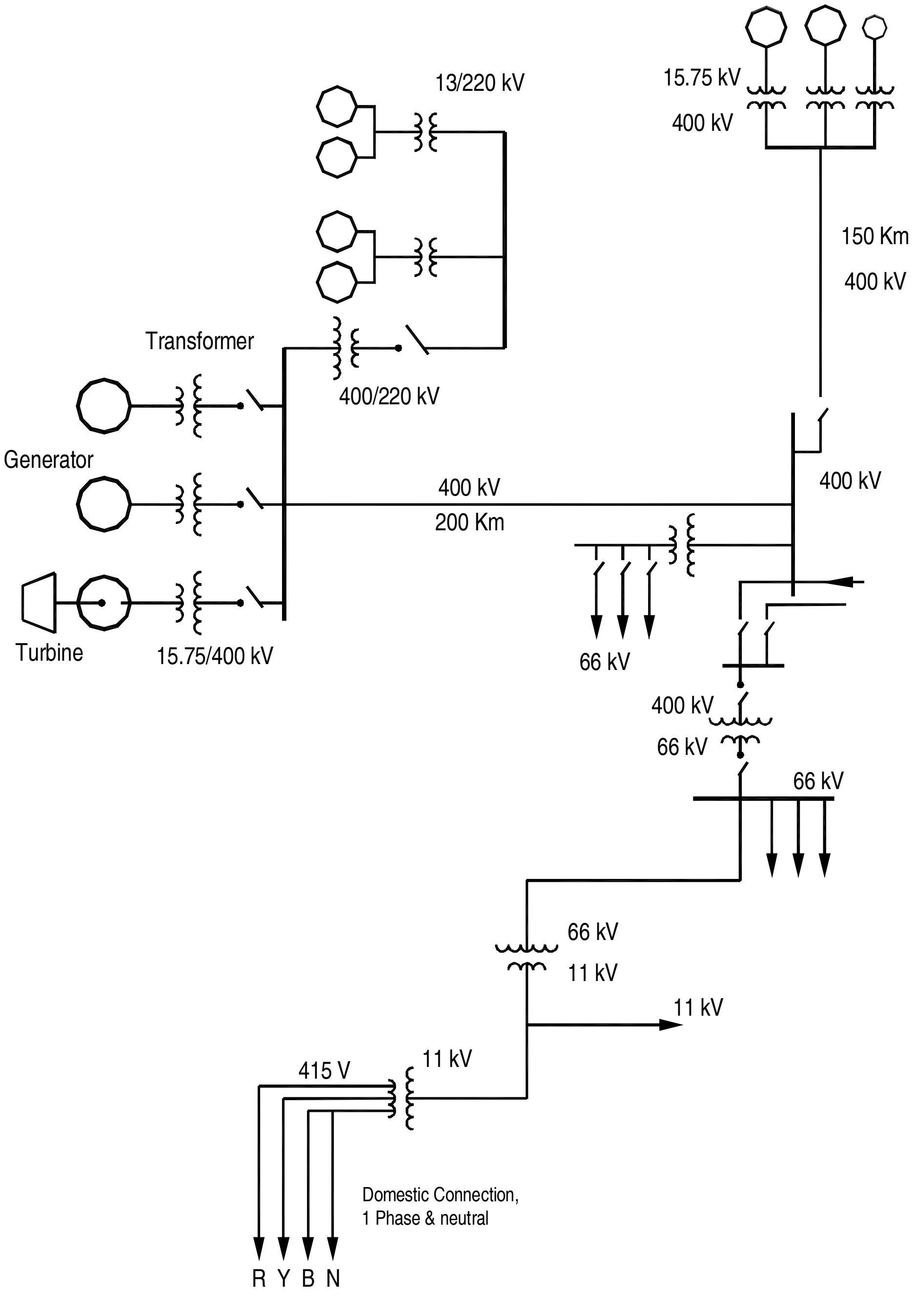


Figure 1. A simple representation of an AC Power System.

An AC power system is a "large pool". Energy generated from different sources are fed into it. Consumers spread all over a state or a region are fed out of it – maintaining a critical balance all the time. System frequency is the index to ensure the balance.

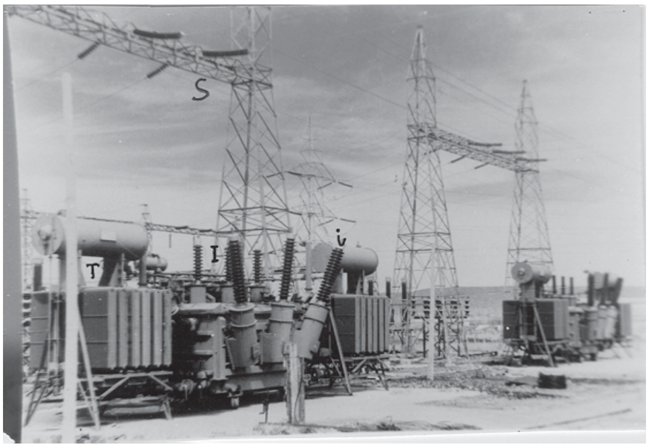
and the other as a standby to allow for breakdown and routine maintenance. It is uneconomical to generate small amounts of power in isolation (except for small hydroelectric units in remote areas) to avoid the cost of duplication.

It is therefore a standard practice to form a large pool and wherever power is generated, it is fed into this common pool. Power required is simply drawn out of this common pool. Such an arrangement not only avoids unnecessary duplication but ensures good quality, economy, stability and continuity of power supply. It is needless to point out in this context that electrical energy can hardly be stored and power generated by all the generators connected to the pool has to be immediately consumed, allowing of course for the losses in transmission and distribution. *Figure* 1 represents a small section of a power system comprising generators, transformers and loads. Huge steel towers supporting three or six lines suspended from insulators are commonly seen in the countryside and also inside some of the cities. A thinner wire at the top of the towers is called the ground wire (providing protection against lightning strikes) and the three or six thicker wires carry the three phase currents.

Generators are usually located at a distance from the load centres. For example in the state of Karnataka, thermal power generated at Raichur Thermal Power plants (7×220MW) is transmitted at 400kV across long distances to cities such as Bangalore where hydroelectric power from Linganamakki Dam and various other sources are transmitted to form the power pool. Power received at 400 kV is stepped down to 220kV and connected to the 220kV grid or stepped down directly to 66 kV. Power at high voltage is next stepped down at receiving stations to 66kV. (*Figure* 2 represents a typical substation). The 66kV grid is interconnected and various substations (and large industries) receive power at 66kV to be stepped down further to 11kV. 11kV lines are taken out radially to various locations for distribution.

An AC power system operates at different voltage levels to ensure maximum operational efficiency.

If the total power generated is given by ΣP_g and the total load is



T represents a transformer. The tank placed above it contains oil. The coils of the transformer are wound around a core (made of steel laminations) and immersed in oil which removes the heat produced in the core and the coils.
I represents an isolator which is a kind of 'switch' used to isolate the station from the grid. Note the huge insulators (marked i) that are used.
The steel structures marked S support the conductors through insulators.

Figure 2. A typical substation.
Courtesy: Kirloskar Electric Company,Bangalore.

ΣP_l then

$$\Sigma P_g = \Sigma P_l + \Sigma P_{loss}.$$

The power loss takes place in the transmission and distribution lines and also in some measure in transformers. If the load demand ΣP_l increases and the generated power is inadequate, the frequency drops below the stipulated 50Hz. This drop in frequency activates governors and more steam (or water) is forced into the turbine to generate more power. If the load drops, the frequency increases and steam (or water) input is reduced. The frequency should not stray too far from the stipulated frequency. If the system cannot extract enough power from the generators, *load shedding* is resorted to. This is undesirable.

3. The Power Situation in India

The capacity of power generation in India has grown more than 40 times during the last 60 years. The total installed capacity including private power generation comes to 1,28,432 MW.

India is divided into five 'Electrical Regions' as shown in *Figure* 3. Some of these regions are interconnected by a power grid. Of the total power generating capacity (or *installed capacity* as it is referred to), the states own about 55%, the Central

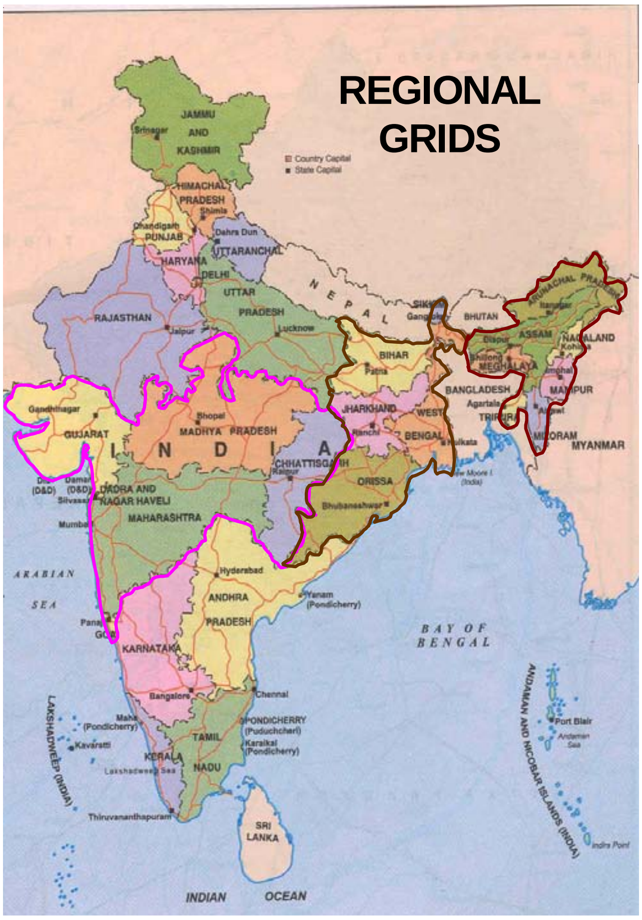


Figure 3.

Authorities own 34% and private organizations own 11%.

Figure 4 indicates the various sources of power that comprise the total installed capacity.

In spite of the impressive growth in the power generating capacity, we are not able to meet either the demand for power or the demand for energy, especially in the rural sector. There is a distinct difference between the two and we have to understand it clearly. There are roughly four groups of consumers and their demands for power are different at different times of the day. The consumption under the four categories are broadly called

a) Domestic consumption,
b) Industrial consumption,
c) Commercial consumption,
d) Agricultural consumption.

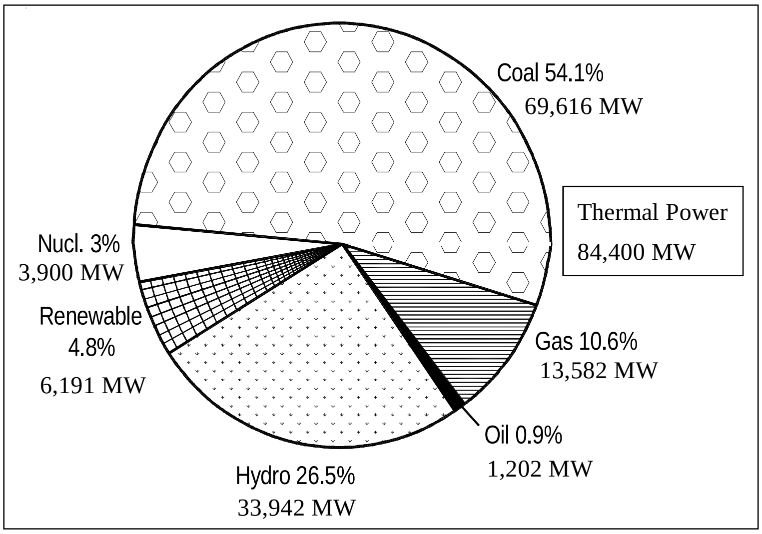


Figure 4. Graphical representation of various sources of power. (Data: 16 February 2007.)

The total demand for a particular day in a city or a state or a region is called a Load Curve. It has usually two peaks as shown in *Figure* 5. The morning peak is largely due to domestic water heating and the evening peak is due to lighting, air-conditioning, switching on of televisions, etc. The near flat portion in the middle of the curve primarily represents industrial and commercial power demands.

A load curve shows hourly demand of electrical power. It is usually a double - hump curve. The area under the curve represents the daily energy consumption.

With economic advancement, the power demands, particularly during the morning and evening, increase or the *Peak Power Demands* increase. The total power that may be generated during these hours may not meet the demand since all generators may not be available to produce the required power. As we have stated earlier, if the demand exceeds the available power generated (minus losses), load shedding has to be resorted to so as not to allow the frequency to drop beyond a certain level. It is obvious that the area under a load curve provides the energy consumed in megawatt-hours or thousand kilowatt-hours or thousand units. The amount of water in reservoirs, or the availability of coal and gas would indicate whether we have enough fuels to provide the demand for energy. A failed monsoon would create a deficit in hydroelectric energy and states like Kerala and Karnataka which depend heavily on hydroelectric power particularly suffer if the monsoon fails.

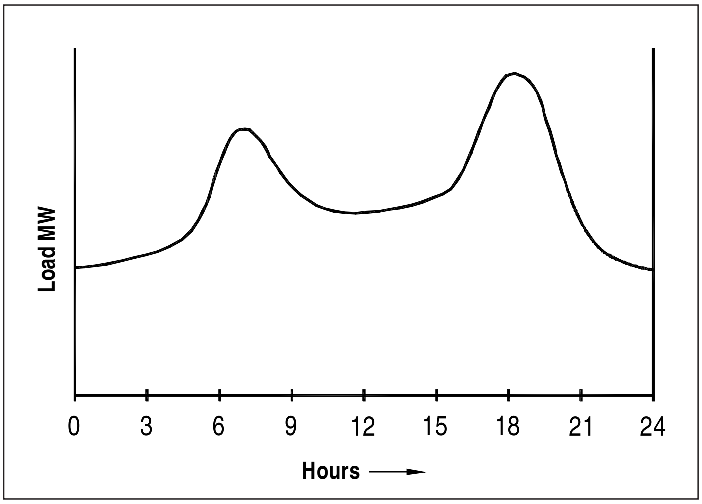


Figure 4. Load curve.

Peak demand	100,403 MW
Demand met	86,425 MW
Deficit	9.3%
Energy demand	572,812 MU
Demand met	519656 MU
Deficit	13.9%

Table 2.

The Power/Energy situation in India during April 2006 and January 2007 is presented in *Table* 1. This is an unsatisfactory situation to say the least and has to be rectified. Thermal power is more reliable and largely meets what is called the 'Base Load' since thermal power does not depend on the vagaries of nature. In our country, we depend rather excessively on coal for power generation and it is well known that burning coal, (Indian coal has 40% ash content) leads to serious atmospheric pollution caused mainly by the production of carbon dioxide. So we have to reduce our dependence on power from coal. Power from gas or nuclear power[1] do not lead to the kind of pollution that results from burning coal.

[1] See P K Kaw, Hymn to Agni – The God of Fire, *Resonance*, Vol.11, No.11, pp.22–39, 2006.

Our priorities should be hydroelectric power generation to the extent possible and non-conventional, decentralized power generation, especially to meet agricultural load which constitutes nearly 30% of our total energy demand.

Transmission and Distribution losses (T&D losses) in our country are very large. The losses are more than 35% which means that we lose about 1/3 of our energy mainly in Ohmic loss (or I^2R loss) as currents flow through the conductors and transformers. This happens chiefly because our distribution networks have grown and are not properly planned and our transformers are often overloaded, leading to large losses.

4. Transmission and Distribution of Electrical Power

Indian power energy situation is unsatisfactory. Transmission and distribution losses are inordinately high. Drastic measures are called for to improve our power sector.

As has been stated earlier high voltage lines carry electricity across long distances. Losses are less in high voltage transmission, but HV lines are costly. In India we have primarily 400 kV and 220 kV transmission systems. High voltage DC transmission has several advantages over high voltage AC transmission. (See *Box* 1). The break-up of HV transmission in our country is given in *Table* 2. The distribution of power takes place in 11kV and 430 volts and that is where the largest amount of losses occur.

Box 1. HVDC

Having lost the 'war of currents', DC transmission has staged a comeback in the form of High Voltage DC (HVDC) transmission. Transmission of bulk power across long distances demands high voltage. Although in India we have 220kV and 400kV for power transmission, Ultra High Voltage AC (UHVAC) transmissions at 500 or 735kV is not uncommon in the west. If instead of AC, we could transmit power at HVDC over long distances it becomes cheaper beyond a certain length, since DC transmission needs two conductors whereas AC transmission needs three (or six); transmission towers and insulation costs are also less. For obtaining HVDC, AC power is stepped up to high voltage, (400 – 600kV). It is then rectified (i.e. alternating current changing direction 50 or 60 times a second is made to flow in one direction) and transmitted. At the receiving end DC is inverted (i.e. turned into 3-phase AC at the system frequency) and stepped down.

HVDC links also enable us to interconnect areas at different frequencies. In India although we use 50Hz, the system frequency often drops below this frequency. Our generation cannot meet the demand and the losses, particularly in the northern and the eastern sector. A national grid helps us to transmit power from surplus to deficit areas. If areas depending mainly on hydropower (Kerala, Karnataka) suffer deficit due to monsoon failure, power from thermal stations in other areas can be transmitted to meet the demand.

Interconnecting the northern and the southern grid by AC lines presents major problems since these areas often operate at different frequencies. Interconnecting large AC areas by AC links presents problems in many countries and HVDC has proven to be cheaper and effective in this respect.

Large, far-flung power systems may be prone to instability. Voltage, current frequencies may oscillate leading to a system collapse. HVDC links often help to alleviate such problems.

765/800kV		2,037 cct.km
400kV	91052 MVA	73,753 cct.km
220kV	152967 MVA	112,901 cct.km
HVDC	3000 MVA	5,872 cct.km

MVA stands for mega volt-ampere and cct.km is the product of the number of circuits multiplied by the distance in kilometers. It may be mentioned in this context that megawatt and megavolt-ampere are not the same. MW = MVA x power factor. If a current flows through a pure inductor, the current lags the voltage by 90^{o} and pf = cos 90 = 0 and wattage is zero although voltage x current or VA is not. No work is expended in sending current through a pure inductor or capacitor and hence no megawatt consumption.

Table 2.

The status of rural electrification in most states in India is very poor.

Close to our residence, we may notice small transformers called distribution transformers, usually mounted on poles. Three phase power is fed to the primary windings of these transformers at 11kV. At the secondary, we have three phase star-connected windings. Three conductors are drawn out of the three phases and one out of the neutral or star point. We have seen earlier in *Box* 2 of Part 1, that $V_{\text{line}} = \sqrt{3}\, V_{\text{phase}}$ in star connection. The voltage measured between two phases or lines is 430 volts and the voltage from line to neutral is 250 volts. Power is supplied to our households by providing one of the three phases and the neutral. This essentially constitutes a single phase supply.

Our distribution networks especially in the rural sector require extensive restructuring to reduce losses to about 15% which is still high, by international standards.

5. Rural Electrification

Electricty was unknown in most of rural India until fairly recent times. Out of nearly 6 lakh villages, 3000 were electrified around 1950 and 18000 Irrigation Pumpsets (IP sets) were energized. The present situation is quite different as shown in *Table* 3.

Irrigation pumpsets that have been energized is close to 1.8 crores which is a massive increase of one thousand times in about 50 years. Excessive use of ground water for irrigation has been causing concern.

No. of villages	593,732
No. of villages electrified	471,360
Percentage of villages electrified	79.4%
Rural households	138,271,559
Having access to electricity	60,180,685
Percentage having access to electricity	44%

Table 3.

6. Conclusion

Polyphase AC system which is to a large extent the legacy of Nikola Tesla, has changed the face of this earth and revolutionized our lives. Generation and utilization of DC would have severely restricted the use of electricity and technological progress.

The demand for electricity has been growing steeply and economic progress is directly dependent on its availability. Although in India, we have made significant progress during the last 50 years in the power sector, there have been major lapses which have landed us in dire distress owing to major shortfalls in power/energy in the country. The state of electric power in the rural areas is still worse and has been retarding rural development to a considerable extent.

Excessive T&D losses, over dependence on coal for power generation, inadequate emphasis on renewable energy resources and wasteful use of electrical energy in our country in driving inefficient machines and lighting inefficient lamps have been contributing towards the inefficient use of the AC power system bequeathed by Nikola Tesla to this world. It is imperative that we rectify our power system by concerted efforts to ensure the development of our country and do justice to the memory of Tesla who towards the sad end of his life derived pleasure only in the thought that his polyphase AC system had helped mankind.

Suggested Reading

[1] D P Sen Gupta, Electricity: AC vs DC, *Resonance*, Vol.2, No.10, pp.46–53, 1997.

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Nicola Tesla was born in Croatia in 1856. Described as a visionary genius, Tesla who harnessed the alternating current we use today is said to be the real inventor of radio. He invented fluorescent lighting and introduced the fundamentals of Robotics, computer and missile science. A loner, he died in 1943 in a New York hotel room where he lived most of his life. Tesla's discoveries changed and continue to change the world we live in. But we know so little about him!