

# **Chapter 2**

## **Voltage regulation in the proposed RWECS**

### **2.1 Introduction**

In the last chapter a RWECS has been proposed for remote area electrification. The components of the system have been selected with objective of simplifying the whole system. There are basically three components in the proposed system. A wind turbine, a wind generator and a power conditioner. The selected technologies are a vertical-axis wind turbine as a wind turbine, a Dual-Stator Axial-Flux Permanent Magnet Synchronous Generator (DSAF PMSG) as a wind generator and an uncontrolled H-bridge three phase rectifier back-to-back connected to an inverter operating at constant modulation indexes as power conditioner.

The use of a PMSG in the proposed system increases the overall efficiency and removes the need for a reactive power supply. Moreover, PMSG has enabled the use of a diode bridge rectifier at the generator-end. Further, the use of a vertical axis wind turbine simplifies the system to the next level owing to the mounting of generator and power electronics converter at the ground level. All the components have simplified the overall

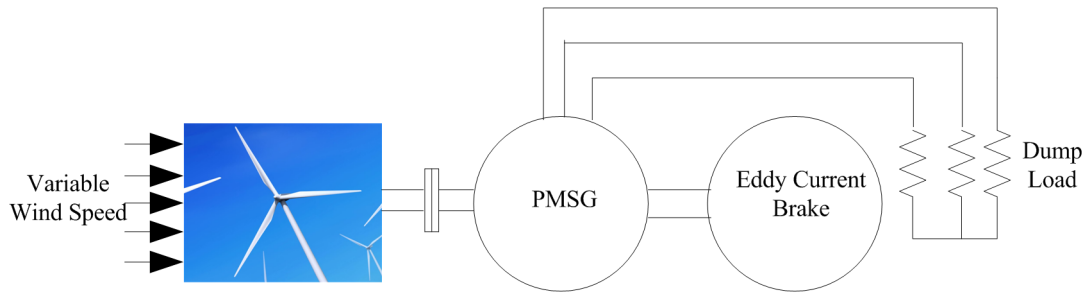


Fig. 2.1 Use of eddy current brakes to restrict the overspeed of generator.

system reducing the maintenance cost and, thus, suitable to be mounted in remote area locations. However, due to highly intermittent wind speed and use of diode-bridge rectifier, produce a variable DC-link voltage at DC-bus bar. Therefore, voltage regulation is one of the significant concerns of the proposed RWECS.

Initially, the excess power in the system at the time of high wind-speed was exhausted in dump resistance connected to DC-link capacitor [84, 85]. Though the method is effective, the excess power is wasted in the dump resistance. The method is useful in the case of gust of wind. Tatis et al. [86] used an eddy current brake in case of overspeeding of turbine-generator at the time of gust of wind by coupling an aluminium disc with the shaft connected to turbine and generator as shown in Fig. 2.1. The generator speed control is another option to operate the turbine at other than optimal tip-speed to wind-speed ratio [65]. Consequently, the power extracted from wind speed is regulated to be equal to the load demand, and therefore, achieving a regulated DC-link voltage. However, the technique requires an active power converter to regulate the generator current for speed control. Another relevant technique, is to use/store the excess power in the system and release it at the time of power shortage [87]. However, the idea increases the installation and maintenance cost and complexity of the system. Another method of obtaining regulated output voltage is to run the system with variable DC-link voltage and operate the grid-side converter in the linear modulation region [88]. However, once the grid-side converter operates in voltage control mode it can not operate in the current control mode and thus,

can not control the real and reactive power flow into the load/grid. All the techniques mentioned above are not appropriate for voltage control in the proposed RWECS. Therefore, an alternate method of system voltage control is considered in the proposed RWECS.

In a PM machine, the magnet fixes the air-gap magnetic field. Many researchers propose to vary air-gap flux in the PM machine to achieve speed/voltage regulation and thus, known as variable-flux permanent magnet (VFPM) machine [89]. This chapter provides a summary of different topologies of VFPM. The methods are as follows

1. Electrically Excited (EE) VFPM
  - (a) Series-flux
    - i. Magnet and coil on the rotor
    - ii. Magnet and coil on the stator
    - iii. Magnet on the rotor and coil on the stator
  - (b) Parallel-flux
    - i. Magnet and coil on the rotor
    - ii. Magnet and coil on the stator
    - iii. Magnet on the rotor and coil on the stator
2. Mechanically Excited (ME) VFPM
  - (a) Altering air-gap length
  - (b) Misalignment of rotors and stators
  - (c) Varying path of leakage-flux

Fig. 2.2 summarises different types of VFPM topologies available in the literature. Following sections elaborate on different types of VFPM topologies.

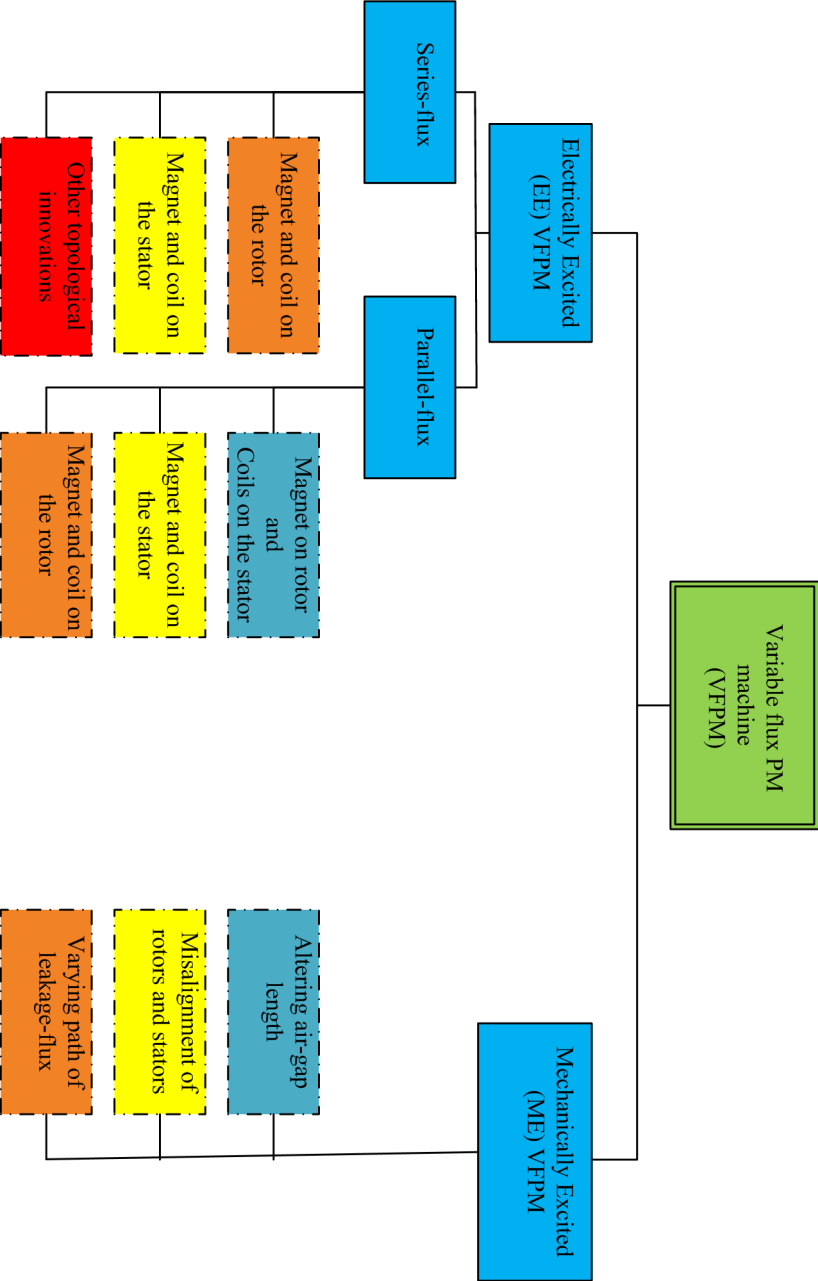


Fig. 2.2 Topological variations in electrically-excited variable flux permanent magnet machine.

## 2.2 Electrically excited Variable Flux Permanent Magnet Machine (EE VFPM)

Any technique that uses an external electric source to vary air-gap magnetic flux (AGF) in a PM machine categorizes under EE VFPM. The techniques are further categorized among series-flux VFPM and parallel-flux VFPM.

### 2.2.1 Series-flux EE VFPM:

In this category of VFPM, machine topology incorporates field coils such that the coil-axis coincides with the magnet-axis. In this configuration, flux from field coils strengthens or weakens the flux generated by the magnet. However, the demagnetizing flux passing through the permanent magnet has the risk of permanently demagnetizing the same. Examples of series coil-based topology are the Doubly Excited Synchronous Machine (DESM) [90] and Doubly Salient Permanent Magnet (DSPM) machine [91, 92]. In DESM, coils are wound on the rotor teeth while permanent magnets are placed on the surface of the rotor teeth, as presented in Fig. 2.3. A DC supply is injected into the rotor coils to produce a magnetic field which could be in the direction of magnet generated flux or reverse. On the other hand, in DSPM, the DC-supplied-coils and magnets are placed on the stator. One advantage of DSPM is the absence of slip rings. However, stator size increases to accommodate the permanent magnets as well as the armature coils. Moreover, in both the configurations, there is a risk of permanent demagnetization of the magnets.

Alternatively, T. Kosaka et al. [93] proposes a hybrid stepper motor with series field weakening without risking the permanent magnets. The geometrical details of the machine are as in Fig. 2.4. In the topology, the permanent magnets is axially magnetized and sandwiched between two rotor sections. The magnetic flux from field coils takes a path from SMC end cap, rotor yoke, and stator yoke. Therefore, the topology achieves

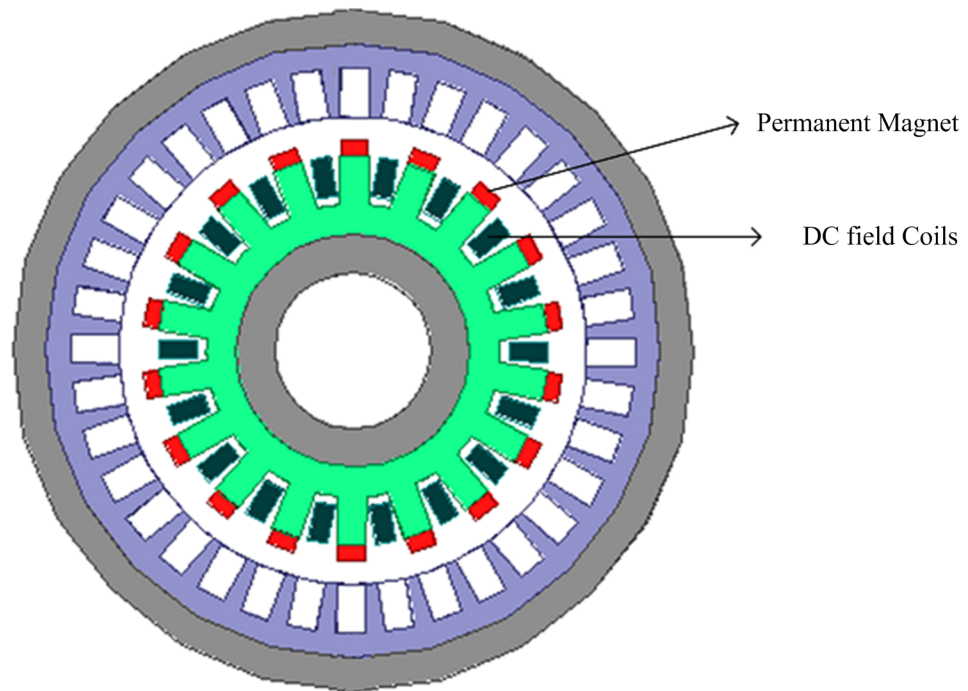


Fig. 2.3 A Doubly Excited Synchronous Machine with permanent magnets and DC field coils on the rotor [90].

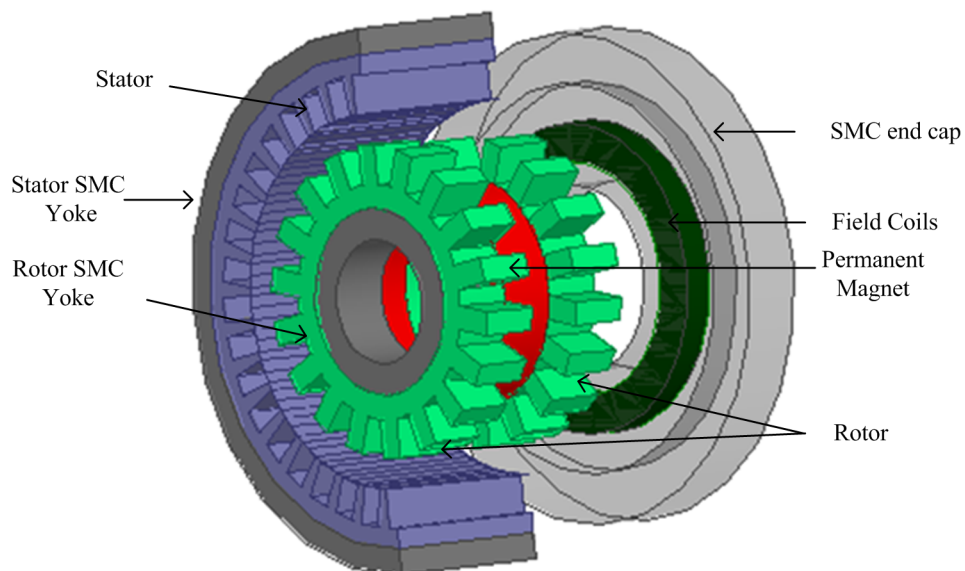


Fig. 2.4 Hybrid stepper motor with series flux weakening without risking permanent magnets.

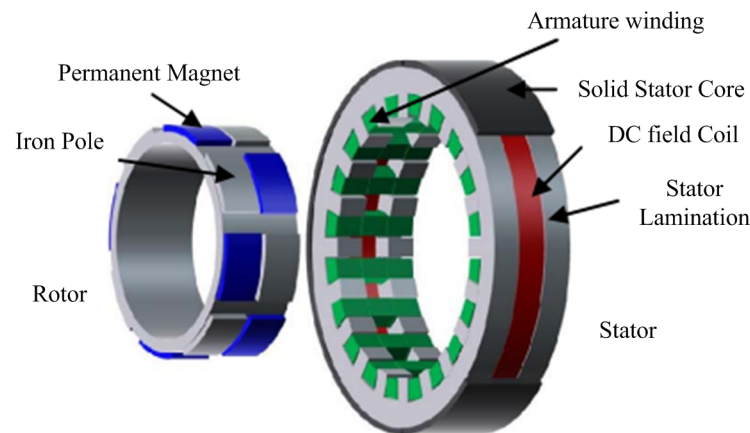


Fig. 2.5 A Schematic diagram of the Consequent pole PM machine.

a risk-free field-weakening. However, the construction is complex, and therefore, the machine might not be cost-effective.

### 2.2.2 Parallel-flux EE VFPM

Parallel-flux-based EE VFPM is more prevalent in the industry owing to its risk-free field-weakening capability. In this category of VFPM, the machine topology incorporates extra coils such that the weakening-flux does not pass through the permanent magnets. However, the field-weakening/boosting is not as good as that of series-coil-based topology. There are many topologies of parallel-coil-based field weakening those are categorized as follows.

**Rotor permanent-magnets and stator field-coils:** The majority of EE VFPM falls under this category. Risk-free demagnetization, reasonable field-weakening, excellent boosting capability, good torque density, and absence of slip-rings in the machine makes it favorable in industries. However, the cost of the machine is on the higher side, owing to its complex geometry. Some of the examples of machines under this category are Consequent Pole PM machine [94–99]. This particular machine uses sandwiched field coils in the stator core, as shown in Fig. 2.5. The field regulation has been found good at the cost of complex

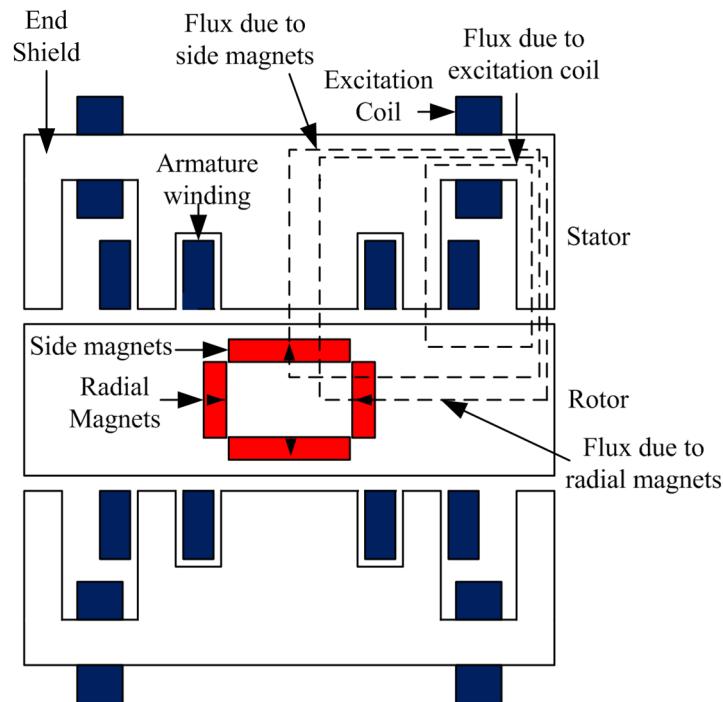


Fig. 2.6 A 2-D diagram of imbricated hybrid synchronous machine.

geometry. Another topology [100–102] uses circumferentially magnetized ferrite magnets embedded into the rotor. Again, the flux control with the use of DC-field coils on the stator is decent, though, at the cost of complex geometry. Another topology, imbricated hybrid synchronous machine [103] has also offered permanent magnet on the rotor and field-weakening/boosting coils on the stator. Here, the DC-field coils have been placed around an end shield as shown in Fig. 2.6. The weakening-flux path do not pass through the magnets and thus, risk-free field-weakening is achieved in the topology. Some more modifications in the topology have been suggested as in High-Strength Undiffused Brush-less [104, 105]. All the topologies have effective flux-boosting and decent flux-weakening at the cost of complex geometry.

**Rotor permanent-magnets and rotor field coils:** Topology under this category are rare due to the need for slip-rings in the machine and its inherent low torque density due to compromising permanent magnets and field coils in the rotor. However, a wide range of flux-weakening/boosting capability is achievable in the topology. Examples of such

machines are Synchronous permanent magnet hybrid machine [106, 107] and axially-split rotor topology [108].

**Stator permanent-magnets and stator field-coils:** Under this topology, permanent magnets and field coils (distributed or concentrated) are placed on the stator. Therefore, slip-rings are not needed though, torque density of the machine is still low because of accommodating the PM and field coils both in the stator. The examples of the machines under this category are doubly salient permanent magnet machine [109–113], switched-flux permanent magnet machine [114–116], and doubly excited dual-stator permanent magnet machine [117]. The advantages of these machines are the robust rotor, absence of slip-rings, and proper field regulation, though, at the cost of low torque density.

Overall, the main advantage of electrically excited field weakening is that one can generate an external magnetic field to weaken/boost the air-gap field. However, the technique is ineffective in low-inductance machines, such as in the Axial-flux machine [118]. Moreover, disadvantages such as low torque density, risk of magnet demagnetization, complex structure, and high cost of EE VFPM machine has led researchers to search for an alternate method of achieving variable flux in the machine. Researchers like Kwon et al. [119] increase machine inductances by using magnetic wedges, fractional-slot windings, and inserting cores around coils overhang. One of the most innovative development is the mechanical method of field-weakening that applies to low inductance machines.

## 2.3 Mechanical Excited VFPM (ME VFPM)

In the ME VFPM technique, the physical geometry of the machine is altered to achieve air-gap field-weakening. External Mechanical actuators alter the geometrical parameters of the machine, such as air-gap length, changing the path of leakage flux, shifting flux barriers, or misalignment between rotors/stators in dual rotors/stators topologies. Though the technique faces the inability to boost the air-gap field, researchers have claimed to

achieve the same by designing the machine for unoptimized geometrical parameters and later altering the geometry to the optimal parameters. There are many patents filed based on MFW techniques [120–123]. The following are brief descriptions of some of the ME VFPM topologies.

### **2.3.1 Altering air-gap length**

Many patents and research papers propose topologies capable of varying air-gap length in the machine [124]. Results presented show a good range of air-gap flux variations. However, to vary the air-gap, the size of the actuator is very large. Thus, the technique is not practical to implement.

### **2.3.2 Misalignment of rotors and stators**

The technique is useful in dual rotors/stators topologies. Here, one of the rotors/stators shifts with respect to another rotor/stator. Fig. 2.7 shows the top-view of a dual-rotor sandwiched-stator axial-flux permanent magnet machine. Here, two pancake-shaped rotor sandwiches the stator. The stator windings are present in the radial slots, and the axially-magnetized permanent magnets are surface mounted on the rotors in north-south fashion. The topology is simulated on ANSYS MAXWELL software to view the magnetic field lines and effects of magnetic field weakening. In Fig. 2.7 (a) the north pole of one rotor aligns with the south pole of another rotor, and therefore, maximum flux-lines link with the stator windings. In Fig. 2.7 (b) the top rotor has shifted. The change in the flux lines paths is to be noted in the simulation plot of Fig. 2.7 (b). Upon the shift, the leakage-flux emerging from one rotor and ending onto itself is observed, and therefore, flux-linkage with the stator winding decreases.

Caricchi Et al. [125] uses a speed-dependent device to shift one of the rotors with respect to the another in a dual rotor AFPM alternator. The same author in [126] uses a

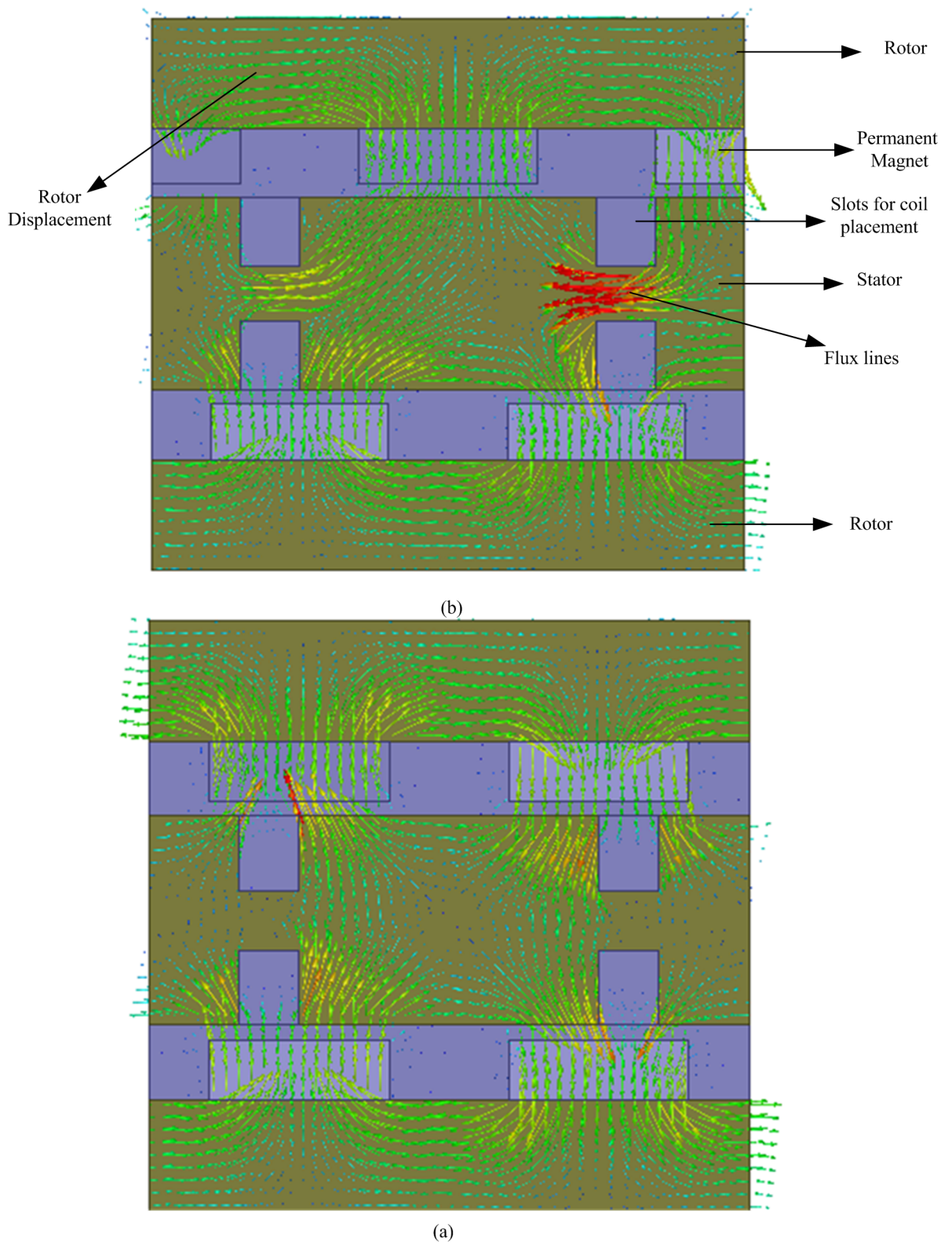


Fig. 2.7 Effect of shift of rotors with respect to other rotor in a dual-rotor topology.

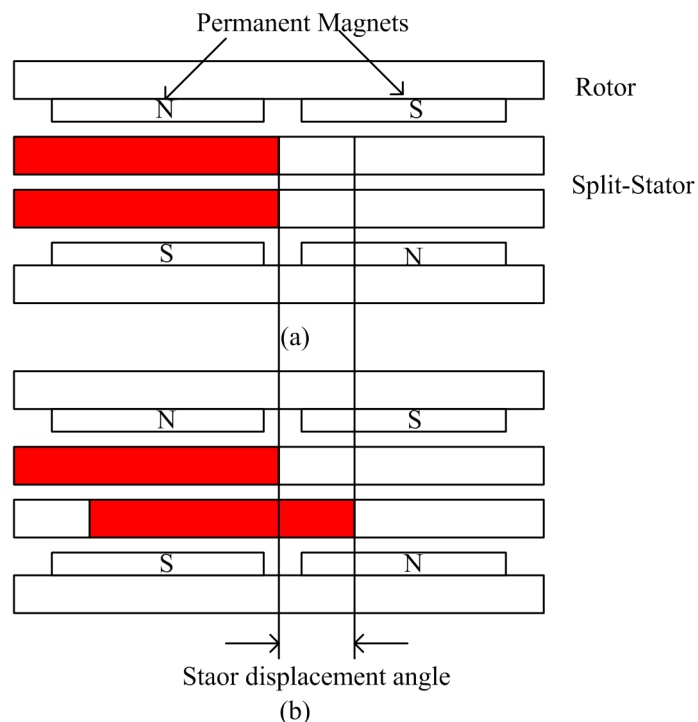


Fig. 2.8 A 2-D diagram of a dual-rotor sandwiched split-stator axial-flux PMSG .

torque-dependent device to create a mechanical-shift between rotors in the same topology. In another paper [67], the stator of dual-rotor AFPM alternator is split and wounded with separate armature windings. Both armature winding connects in series, and stators displace angularly to create field weakening effect in the generator. A schematic 2-D diagram has been shown in Fig. 2.8 An external mechanical actuator shifts one of the stators with respect to the other. The same method is implemented in a dual-stator sandwiched rotor AFPM generator [127]. Here, one of the stators is fixed, and another stator is made movable to create a mechanical shift between the same as shown in Fig. 3.17.

Another paper [128] introduces a switched-flux permanent magnet generator topology. In the topology, the inner stator consists of internal PMs (IPM), and the outer stator consists of the armature winding. The rotor is made of iron bars fixed in resin, which rotates between the two stators as shown in Fig. 2.9. The field-weakening in the machine is

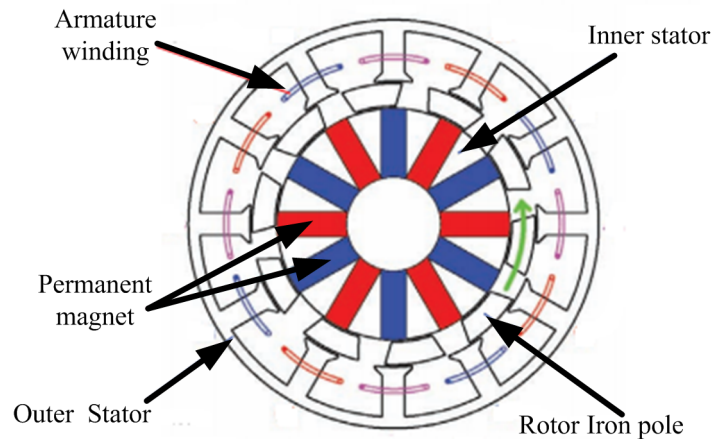


Fig. 2.9 A 2-D diagram of a switched-flux permanent magnet generator [128].

achieved by shifting the inner stator to align/misalign with the outer stator. The technique is effective in reducing flux-linkage with armature winding up to 50 %.

### 2.3.3 Varying path of leakage flux

Another set of techniques by different researchers suggest varying the flux-leakage path in a PM machine in place of directly compensating the air-gap flux. However, the technique applies only to an internal permanent magnet (IPM) machine. Owen Et al. applied [129] the field-weakening technique in a topology with IPM on the stator. An extra leakage-flux in the machine is drawn by shorting PM on the stator using a magnetic short-circuit back iron bar beside the stator-yoke as shown in Fig. 2.10. The technique is useful with achievable flux weakening up to 70 %. However, the setup needs an external actuator and also increases the size of the machine. On the same lines, extra leakage-flux is drawn in topologies having IPM inside the rotor by introducing side-plates to the rotor and shifting the same to varying extent of field-weakening. The field weakening achieved is up to 30 %.

Topologies consisting of IPM in the rotor have seen more innovative designs [130, 131] owing to the centrifugal forces on the components of the rotor. Ma Et al. insert

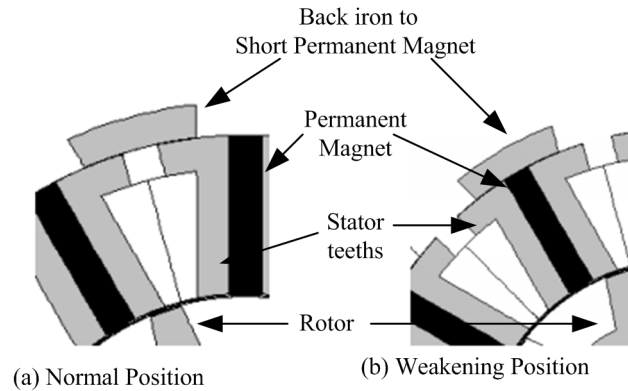


Fig. 2.10 2-D diagrams of mechanically switched-flux PM machine with different field-weakening position [129].

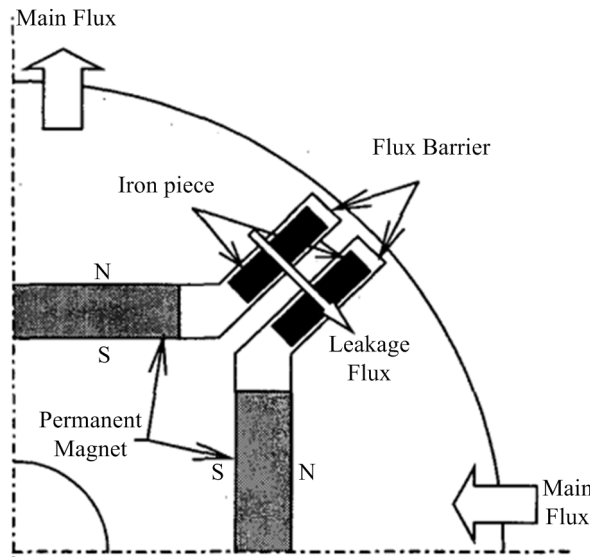


Fig. 2.11 2-D diagram of the rotor cross-section of an inserted PM on rotor type PMSG topology showing adjustable iron bar for field-weakening in the same [130].

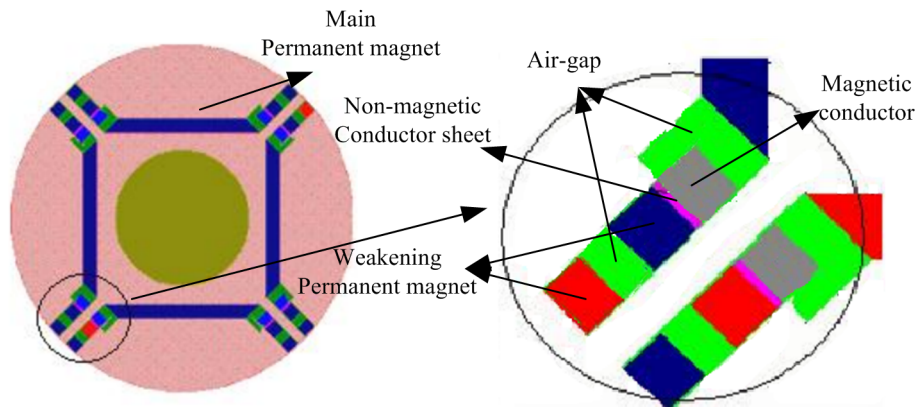


Fig. 2.12 2-D diagram of the rotor cross-section of an inserted PM on rotor type PMSG topology showing adjustable weakening permanent magnets for field-weakening in the same [131].

[130] an iron bar in the flux barrier present inside the rotor. The length of the iron bar shifts to decrease the PM-generated air-gap flux and increasing the d-axis inductance as shown in Fig. 2.11. However, in the topology, insufficient flux-leakage is drawn out of the magnet, and the amplification of armature reaction in the machine achieves the basic air-gap field-weakening. This poses the risk of permanent demagnetization of the magnets. However, a decrease in d-axis flux has been observed to be 50 %.

Another technique [131] uses extra field-weakening magnets and some movable magnetic components. The field-weakening magnets and the magnetic components are such arranged that the overall effect of reaction force between the magnets and the centrifugal forces moves the movable magnetic component as shown in Fig. 2.12. The movement of the magnetic component decreases the leakage-flux reluctance in the rotor. Thus air-gap flux varies but only in the range of 8-9 %.

## **2.4 Selection of field weakening technique in the proposed RWECS**

As per discussion held in the previous chapter, the proposed RWECS chooses a Dual-Stator Axial-Flux Permanent Magnet Synchronous Generator (DSAF PMSG) as a wind generator. Owing to the low inductance of the chosen wind generator topology and need of a simple field-weakening technique, an ME VFPM is found to be most suitable. Moreover, the presence of dual-stators and easy access to both outer-stators enables the shift of stators with respect to each other, as to be the most sophisticated technique of varying the flux-linkage with the stator windings.

The proposed system is akin to working of an Induction regulator [132]. In Induction regulator the alignment of rotor and stator changes. Although in Induction regulator the power is not generated. Here in the system the power is being generated by coupling the

generator with a wind turbine. The voltage regulation of the generator at variable wind speed is achieved by field-weakening of the generator. The field weakening is caused by mechanical alignment of both the stators of the generator. A closed feedback system is designed to alter the orientation between two stators as per the intermittent wind speed and regulate the generator output voltage.

## **2.5 Conclusion**

This chapter discusses the different types of alternate field-weakening system in a permanent magnet machine. In the previous chapter, the proposed RWECS uses a DSAF PMSG as a wind generator. The effectiveness of mechanical field-weakening system in the low-inductance machine and its ease of implementation makes it to be the most suitable for the chosen generator. The mechanical field-weakening in the machine is achieved by shifting one of the stators of the dual-stator generator with respect to others.

The next chapter provides details of the fabrication of a proof-of-concept DSAF PMSG. An experimental setup of the proposed RWECS is fabricated. Testing of the same is conducted, and experimental results have been shown supporting the principle of the concept of this thesis.