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ARTICLE *in* IBIS · SEPTEMBER 1994

Impact Factor: 1.86 · DOI: 10.1111/j.1474-919X.1994.tb01116.x

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IBIS 136: 412–425

Bird interactions with utility structures: collision and electrocution, causes and mitigating measures

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The causes of collision and electrocution accidents involving birds and power lines, and measures to mitigate such accidents, are reviewed. It is convenient to group the causes according to (1) biological, (2) topographical, (3) meteorological and (4) technical aspects. As regards collisions with power lines, the important biological variables are connected with the morphology, aerodynamic capability, physiology, behaviour and life-history strategies of birds. To understand the electrocution problem, the relationship between body size and electrocuting installations must be considered.

Removing earth wires (and modifying earthing methods), modifying line, pole and tower design, installing underground cables and conspicuous marking of lines, poles and towers are important measures for tackling the problems. The route planning process should include careful mapping of (1) topographical features which are leading lines and flight lanes for migrating birds and/or are important for local movements of resident species, (2) topographical elements such as cliffs and rows of trees that force birds to fly over power lines, (3) primary ornithological functions or uses of the area to avoid key areas for birds and avoid separating these areas and (4) local climatic conditions (including seasonal variations) like fog frequency and prevailing wind direction. The outcome depends largely on a combination of these factors.

Objective assessment of the effects of mitigating measures, in particular wire marking, is required. The mitigating efforts should be directed against species known to be potential collision victims, and their design should be the result of a careful analysis of the biology and ecology of the target species.

Because of the cumulative effects of negative impacts on bird populations today and the alarming number of species with endangered or vulnerable status being killed in connection with utility structures, the problem deserves increased general awareness.

It has become increasingly important in ecological impact analysis to pinpoint problems from the perspective of biology and conservation as well as economical and industrial development. The problem of avian interactions with utility structures demonstrates how biologists, conservationists and engineers have to cooperate to achieve common goals—safety for birds and reliable power supply.

Birds create economic problems by causing breaks in energy supply through collision and electrocution. Birds fly into overhead wires and are electrocuted; endangered and vulnerable species are killed. Each year, a huge number of birds are crippled and killed, often suffering an inhumane death.

The range of interactions between birds and electricity supply is broad, and the topic was considered many years ago (Michener 1928). Birds collide with phase conductors and earth wires and are electrocuted at a variety of installations. The use of transmission-line towers for nest building, roosting and prey surveillance by birds may lead to breaks in electrical supplies with consequences to a range of sectors, e.g. computerized processes in industry and communication systems (cf. Nagel 1978).

The significance of collision and electrocution accidents to bird populations is a question addressed by several authors (e.g. Avery 1978). Although emphasis should be put on the overall biological and ecological aspects because of the endangered bird species involved in these types of accident, the cumulative effects of negative impacts on bird populations today justify increased general awareness of the problem.

The objectives of the present paper are to review the topic of bird collision and electrocution and to look at the variety of governing factors which make birds collision and electrocution victims. The planning efforts and efficiency of technical alternatives to minimize the problem are also addressed. The paper has a global geographical perspective.

Table 1. *Answers received from 175 Norwegian power companies in response to a questionnaire asking about various aspects of the interaction between birds and power supply*

Question	Yes	No	Unanswered
Have birds caused breaks in the power supply in your district?	77% $n = 134$	14% $n = 25$	9% $n = 16$
Are birds regarded as a problem in your supply district?	55.5% $n = 97$	43.5% $n = 76$	1% $n = 2$
Have installations been identified causing particularly frequent electrocution?	73% $n = 127$	19% $n = 34$	8% $n = 14$
Have technical improvements been made?	34% $n = 60$	64% $n = 111$	2% $n = 4$

The issue is especially focused on in the U.S.A., South Africa and Europe, but the problem will increase dramatically in developing countries.

LITERATURE ON COLLISION AND ELECTROCUTION

The literature on this subject is comprehensive (see Avery *et al.* 1980), but it is not easily accessible since much is found as unpublished reports and in national or regional periodicals, where some reviews also have been published (Lee 1978, Thompson 1978, Longridge 1986, Bevanger & Thingstad 1988). The reports typically have been prepared by biologists in the employ of power companies. However, the bulk of the literature consists of notes and brief reports in ornithological periodicals concerning observations of single accidents. Some data in this study were collected through a questionnaire sent to Norwegian power companies (Table 1).

THE COLLISION PROBLEM

In many areas, birds constantly face threats through colliding with power lines, telegraph wires, television and radio transmitters and related wires, fences, windows, wind turbines, gas flames, lighthouses, aircraft, cars, trains, etc. These man-made obstacles may be grouped into three categories: (1) "passive" threats (overhead wires, fences, television and radio transmitters, wind turbines, windows, (2) "active" threats (aircraft, cars, trains) and (3) "confusing" or "trapping" threats (lighthouses, gas flames).

To understand why birds fly into power lines, the activities resulting in the collisions have to be identified. Completely different factors need to be considered and synthesized. It seems convenient to group these into (1) biological, (2) topographical, (3) meteorological and (4) technical aspects. It is usually beyond the power of man to carry out modifications or take mitigating steps in the case of 1, 2 and 3. However, knowledge relating to these factors should be applied in the power-line route planning to reach the best possible solution. The technical aspects are open to good ideas which may appear.

Biological aspects

Although birds are masters of the air, morphologically and aerodynamically fitted for airborne movement, life in the air is a finely tuned balance within a maze of hazards. Reports of birds being unable to cope with the elements exist—e.g. seabirds tipped into wave crests by severe turbulence or sudden gusts (Elkins 1988). However, the evolutionary process that gave these animals superiority in the air has only recently been influenced by man-made constraints. Thus, there are limits to the ability of birds to cope with artificial obstacles.

Willard (1978) stressed that birds often hit wires when preoccupied with landing, hunting or fighting. His statement finds support in the numerous observations of catastrophic incidents and mass kills through collisions (e.g. Blokpoel & Hatch 1976, Schroeder 1977). However, the variety of bird species identified as collision victims indicates that a range of biological and external factors must be considered in concert to understand why a specific bird species or an individual is more likely to fly into overhead wires.

Flight behaviour and vision are two important aspects to be considered when evaluating the "collision potential" of a bird species. Wing loading (ratio of body weight to wing area) and aspect ratio (ratio of wing span squared to wing area) are crucial for bird flight performance (e.g. Norberg 1990). Rayner (1988) divided the major groups of birds into six main categories according to aspect and loading: marine and thermal soarers, aerial predators, diving birds, water birds and "poor" flyers. Soaring and slow-flying species can be expected to be less vulnerable to collision hazards than fast, strong flyers (i.e. species with high wing loading). Typical collision victims like rails and grouse are classified among the "poor" flyers, indicating this to be an analytical method for identifying some bird species as particularly vulnerable to collision with overhead wires.

Research into bird vision has revealed a great variety of adaptations among various groups (Martin 1985, Schmidt-Morand 1992). The majority of bird species are classified as central monofoveal (Sillman 1973). These have a single fovea (an area on the retina of very good acuity or resolution due to the high visual cell density; Martin, 1985) located near the centre of the retina. However, typical predators or hunters (e.g. hawks, bitterns and swallows) have two areas (bifoveal retina) (Sillman 1973, Schmidt-Morand 1992). The bifoveal retina and frontal eyes of a falcon allow about 60° binocular or three-dimensional perception but at an expense of 200° blind zone (Schmidt-Morand 1992). An extensive blind zone may help to explain why even some raptors with highly binocular vision fly into power lines. Some birds, e.g. several gallinaceous species (Sillman 1973), lack or have a poorly developed fovea; they are afoveal. This is especially interesting since most Norwegian tetraonids seem particularly vulnerable to collision with power lines (Bevanger 1990).

Behaviour and life-history strategies differ, and birds active in periods with poor light (e.g. twilight at dawn and dusk) and nocturnal species are expected to be vulnerable to crashing into artificial obstacles (cf. Elkins 1988, Martin 1990). Activity patterns when the light is poor are a major and complex aspect of bird behaviour, and flight under such conditions does not take place without risks; "nocturnal behaviour in birds requires an unobstructed habitat" (Martin 1990, p. 115).

Light conditions depend on latitude and season. Midwinter daylight (including twilight) at 66°N is 62% of that at 45°N (Elkins 1988). Theoretically, resident species at high latitudes should suffer higher mortality caused by colliding with power lines during the winter, and collision frequency should increase with increasing latitudes because light conditions deteriorate with increasing latitude during that period of the year. Non-resident species breeding at higher latitudes than the Arctic Circle (i.e. 66°N) have not experienced nighttime light levels for many weeks when starting the southward migration in the autumn and juveniles have never experienced them at all. On the other hand, spring migrants move towards lighter conditions. To speculate about whether autumn migrants are more vulnerable to collisions than are spring migrants, however, is not particularly constructive, as opportunities for obtaining answers are limited. But migratory species cross numerous power lines on the way to and from their wintering grounds and, in general, may be expected to experience greater risk of collisions than resident species.

Some resident species have lek periods (e.g. several tetraonids), when they congregate in numbers. The movements (low flight) to and from the lekking grounds may pose a threat of collisions. Many species may be classified as occasionally nocturnal species (Martin 1990) during the courtship display period. During the mating season, some species perform display flights which include "hazardous" dives that may have disastrous consequences in areas criss-crossed with wires.

Species spending extensive periods of time in the air, e.g. avian predators, might be supposed to face a greater collision hazard than ground-dwelling species. In general, raptors seem to be involved in collisions infrequently (Olendorff & Lehman 1986), but some species are vulnerable to collisions because of their hunting behaviour—attaining high speeds when following prey (e.g. Peregrine Falcon *Falco peregrinus*, Gyr Falcon *F. rusticolus*, Hen Harrier *Circus cyaneus*, Golden Eagle *Aquila chrysaëtos*, Goshawk *Accipiter gentilis*) (Bevanger & Thingstad 1988, Rose & Baillie 1992).

Topographical aspects

It is difficult to judge the effect of landform on bird flight. Distinctions must be made between macro- and microform. The classic term "leading line" (Geyr von Schweppenburg 1929, 1963) describes macroforms that are important for migrating birds, e.g. a coastline, and which may create central flyways. General knowledge about leading lines for navigation purposes during either local or long-distance movements (e.g. Mueller & Berger 1967, Alerstam 1977) may be important for explaining collision "hot spots". "Flight lane" may be a more convenient term to use with respect to local movements. Flight lanes may be determined by slight depressions in the terrain or strips of unforested fen allowing birds to fly at a lower altitude. A trained ornithologist may be able to predict leading lines and flight lanes on the basis of topographical features.

A power line located between a feeding area and a roosting site of wetland birds can be disastrous (e.g. McNeil *et al.* 1985, Crivelli *et al.* 1988), especially when only a short distance separates them so that the birds only have to make a short flight at the critical height. Birds that depend upon specific lek grounds in spring (e.g. Capercaillie *Tetrao urogallus*, Black Grouse *Tetrao tetrix*) are vulnerable if power lines or wire fences are located close by, since they often make short flights at the critical altitude (Bevanger 1990).

Power lines passing near "key" ornithological habitats should be located close to the bases of cliffs or near protective rows of trees, which force birds to fly over the wires (see Thompson 1978). Forest vegetation along the power-line corridor should not be removed. Locating a power line close to tall buildings, bridges and other man-made structures may also reduce the collision risk (see Thompson 1978), as well as locating power lines along main roads where birds usually increase their flying height. To achieve optimal detectability, it is important to consider carefully the contrast of the wires against the background.

Research on collision hazards for tetraonids in boreal forest habitats in central Norway (Bevanger 1990) indicated that collision "hot spots" appeared in areas where phase conductors were located close to the tree tops. Increased risk of collision also seemed evident where power lines crossed a rise or depression, while few collisions took place where dense forest was present on one or both sides of the clear-felled corridor.

In addition to the principle of forcing an increase in flying height, lines should be placed parallel to major flyways (Scott *et al.* 1972). These points were illustrated by Thompson (1978), who stressed the importance not only of locating lines along topographical features like mountain gaps, river valleys and ridges that tend to channel or concentrate flight paths but also parallel to prevailing wind directions to reduce the possibilities of birds being blown into the wires. However, in practice, routes are dictated by economic factors, not by biological considerations.

Meteorological aspects

Although bird migration is part of a life-history strategy and thus is a biological aspect, it seems convenient to discuss it in connection with meteorological aspects, since it seems to be greatly influenced by weather conditions and atmospheric structure. Flight pattern and variation in elevation are important factors when probabilities for collision are being judged. Radar studies and visual observations from the ground (bird observatories) and from aircraft (e.g. Alerstam & Ulfstrand 1974, Pennycuick *et al.* 1979, Richardson 1979) have considerably increased our knowledge of these factors in recent decades. Kerlinger & Moore (1989) have reviewed the effect of variations in atmospheric conditions on bird migration, and Martin (1990) has reviewed the sensory problems of nocturnal birds, including night migrants. Martin (1990, p. 34) states that "night migration is probably by far the most extensive nocturnal behaviour that birds exhibit".

Powered flyers normally migrate at night or in the early morning (before 1000h), whereas soaring migrants fly at midday (Kerlinger & Moore 1989). Large, fast-powered migrants like waterfowl and waders are more likely to migrate in daytime than small passerines. The main factors determining these patterns are air temperature and wind conditions. Martin (1990) stressed that there is no evidence for "exclusively nocturnal" migratory species and that most nocturnal migrants also may fly in daytime. It is generally difficult to make firm statements when talking of bird migration patterns and strategies.

Weather conditions influence migrants as well as resident species, and it is important to distinguish between resident populations and migrating birds when effects of atmospheric structure and weather conditions are considered. Dull, overcast weather and especially thick fog or wind are known to change the general flying height, usually forcing birds to fly at a lower altitude, even close to the ground (Avery *et al.* 1977, Elkins 1988, Kerlinger & Moore 1989). Some of the most dramatic collision mortalities against man-made structures have taken place under such conditions (e.g. Kemper 1964, Aldrich *et al.* 1966, Verheijen 1981). With strong surface winds, most birds "go to ground to avoid the risk of collision with obstacles" (Elkins 1988, p. 43). Powered migrants in general change altitude with wind direction and speed (Kerlinger & Moore 1989). Head winds cause birds to fly lower than those flying with following winds (e.g. Bergman 1978, Perdeck & Speek 1984). From an energy point of view, it is preferable to fly low into head winds because the wind speed is lower near the ground. Local decreases in visibility owing to fog, mist, rain or snow makes overhead wires difficult to see.

The meteorological, as well as biological and topographical, aspects are important in the power-line route-planning process. Careful route planning is among the best and least expensive ways of reducing bird collisions (cf. Miller 1978, Thompson 1978). Detailed knowledge of local birds and migratory flight lines is crucial. In general, ecologically sensitive areas such as wetlands, where birds congregate to nest, feed, roost, migrate or overwinter, must be avoided. Intermittent wetland is a good example of a habitat which should be avoided but which is not always an obvious key area for birds. It is mainly productive when it becomes flooded, yet it may be dry most of the time and not considered important when field planning is carried out. Increased knowledge about what characterizes a high-hazard location hopefully will help select optimal power-line routes. Power-line route planning, therefore, is not only a technical and engineering task but one for which ecologists must be consulted. However, there are several conflicting interests (e.g. economic concerns, opportunities for land-use, aesthetic/visual problems) when the choice of a power-line route is to be made.

Technical aspects

Although the heights of flying birds will never be accurately predictable parameters due to a variety of modifying factors, lower collision frequency can be achieved through line design modifications, e.g. by adjusting phase conductor height, wire diameter, spacing, configuration and number of circuits. Between pylons, phase conductors normally sag under their own weight, perhaps to half the height of the supporting structures, exposing birds to collision risks at several flying heights. Metal expansion, moreover, causes the wire height to vary with air temperature. There is least risk of collision with power lines passing through forested areas when they are situated below the height of the tree canopy, since most birds normally fly above tree-top height (Bevanger 1990). However, this increases costs as more poles are necessary to provide shorter spans and retain minimum ground clearance.

A flat-line configuration is preferred to a vertical one, e.g. multiple conductor planes in stock or delta configuration should be avoided (Fig. 1). In Holland, a change to a "gateway-tower" construction with only two levels of phase conductors and earth wires resulted in a decrease in the number of avian victims found (Renssen *et al.* 1975). Several Norwegian power companies emphasized in their response to questionnaires that triangular configurations are especially liable to cause bird collisions (Table 1).

It may be wise to group power lines in a common corridor (Thompson 1978), resulting in better visibility and occupation of a smaller area. Flying birds then have to make only one manoeuvre to avoid the wires. Separated power lines force birds to make repeated avoidance manoeuvres, thus increasing the collision risk. On the other hand, wires situated in groups at different heights represent an increased collision risk for birds flying in bad weather and poor visibility.

Norwegian power companies are now discussing the use of a new type of insulated phase conductor for 22-kV distribution lines. These conductors (PEX cables) withstand short periods of contact without causing a flashover and require narrower clear-felled corridors. This cable may have positive effects with regard to bird collisions and electrocution. In general, aerial bundled cables are supposed to offer a reduction in the collision hazard in high risk areas, being rather more bulky and visible.

Conductive components of utility structures are generally earthed, and earth wires are frequently located above or

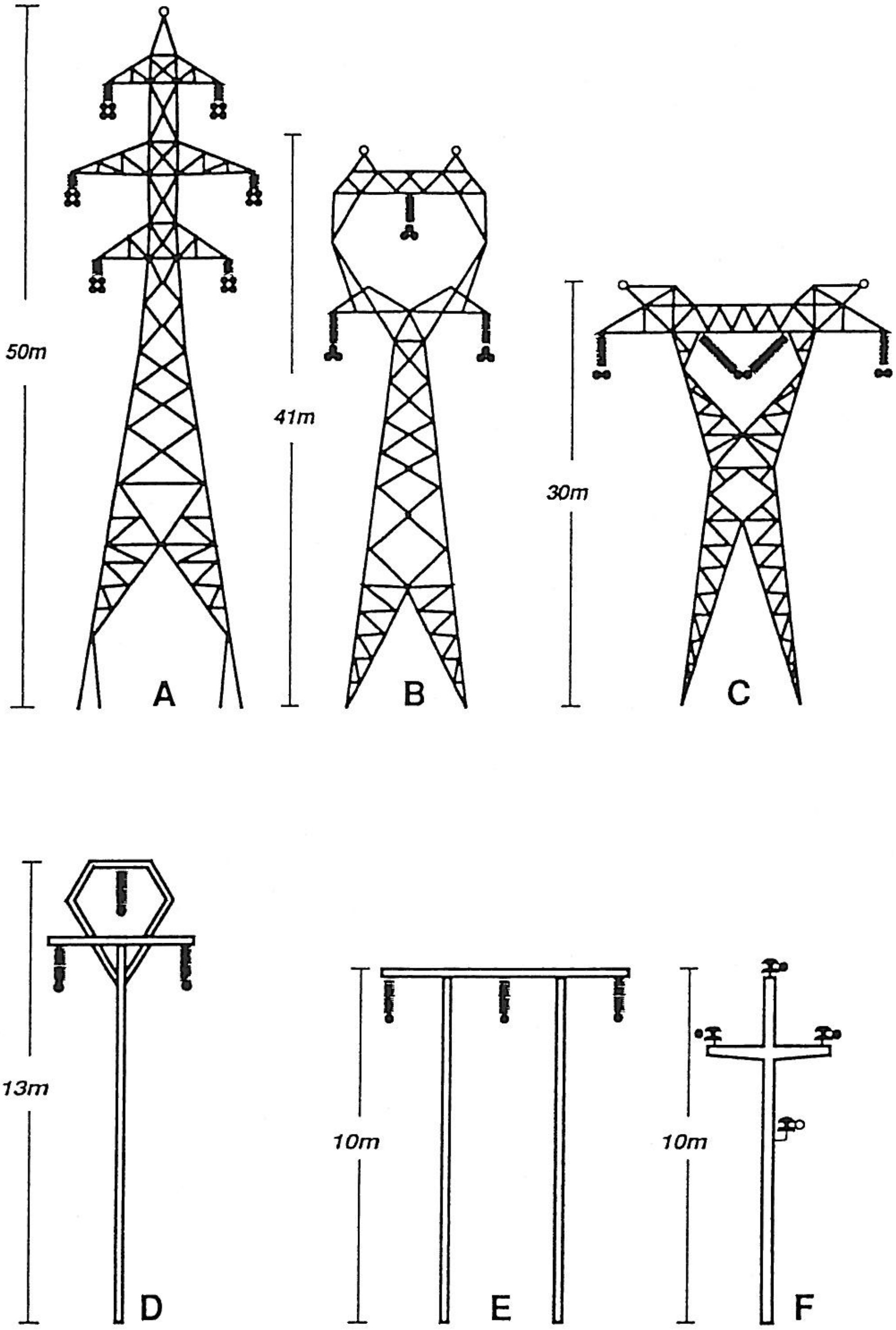

Figure 1. Design of typical transmission and distribution line towers and pylons. (A) Double circuit stack configuration, quadriplex (500 kV); (B) Single circuit delta configuration, triplex (200 kV); (C) Single circuit flat configuration, duplex (500 kV); (D) Single circuit "kite" configuration, simplex (88 kV); (E) Single circuit H-frame (wood structure, simplex, 132 kV); (F) Single circuit triangular configuration, wood pole, 22 kV, where the conductors are attached to top-mounted pin insulators and an earth wire is located below the conductors. Conductors are indicated with filled circles, earth wires with open circles. Structure heights are approximate values.

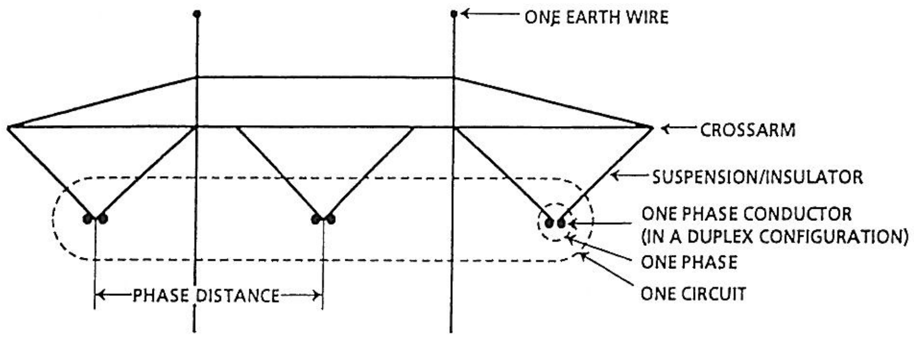

Figure 2. Sketch of the upper part of a high-voltage transmission line tower (longitudinal section). Duplex configuration specifies that the conductors are bundled in pairs (after Bevanger & Thingstad 1988).

below the phase conductors. Removing earth wires has been found to reduce collision frequency (Beaulaurier 1981). Several authors have stressed that earth wires are particularly likely to cause bird collisions (e.g. Meyer 1978, James & Haak 1979, Willdan Associates 1982). There are eyewitness accounts of swans which have managed to avoid phase conductors in time, only to crash into the top wires which were thinner and less visible.

The transmission system in Sweden now employs thicker earth wires (Lindgren 1984). However, empirical data to show whether or not there is a general inverse correlation between collision rate and increasing diameter of phase conductors or earth wires are lacking. Heavy mortality of tetraonid species in central Norway was related to distribution and transmission lines without wires (Bevanger 1990). No differences were found between Willow Ptarmigan *Lagopus lagopus* mortality rates caused by 22-, 66- and 300-kV phase conductors in southern Norway (Bevanger & Sandaker 1993).

There are millions of kilometres of power lines throughout the world, mostly constructed when birds and environmental issues were rarely on the agenda. Thus, the question of what to do to a collision hot spot inevitably arises. The usual answer is wire marking. Wire marking (including acoustical devices) has received increasing attention in recent years, and a "device industry" has been established. An impressive diversity of warning devices attached to earth wires and/or phase conductors has been developed.

(1) Wire coating (coloured plastic covers, painting of wires). Successful use of wire coating has been reported from Norway (Folkestad 1980). Increasing reports of Whooper Swan *Cygnus cygnus* collisions resulted in the use of a phosphorescent plastic cover on a critical section of the line concerned. The phase conductors of another section were painted signal red. More attention should be given to the colours of marking devices. In poor light, the visual pigments of the avian eye absorb, at the most, nearly 500 nm (i.e. the blue-green part of the spectrum). There is strong evidence that maximum absorption in daylight conditions is about 560 nm (yellow-green) (Sillman 1973). Manufacturers of marking devices should take this into account and design or colour their devices specifically for the target species.

(2) Physical enlargement (balloons, spheres, spirals, plastic strips, etc.). Marking devices of various shapes and colours can be attached to phase conductors and/or earth wires (e.g. Renssen *et al.* 1975, Koops 1985). Plastic bird flight diverters (cf. Bevanger & Thingstad 1988) are the most common device and appear in a wide variety of shapes and colours. On transmission lines with duplex, triplex or quadriplex configuration (Figs 1 and 2), the single lines of the phase are kept apart by a spacer, which serves as a marking device. Such wire "bundles" are more visible than single wires (cf. Renssen *et al.* 1975).

(3) Silhouette/predator scaring methods. As many wire strikes take place in poor light, devices visible at these times are preferable. Dutch ornithologists have experimented with raptor silhouettes (Heijnis 1980). The most effective silhouette (falcon/hawk) resulted in a significant decrease in collision frequency, and the effect of the silhouette did not decrease over time. Scaring devices for repelling birds can be expected to work for migrating species moving through the area, i.e. they do not stay long enough to become accustomed to them.

(4) Use of light. Devices in categories 1–3 have limited effect on nocturnal species and diurnal species migrating at night. Illumination using high-intensity light is not an alternative. Numbers of birds are killed along the Scandinavian coast when colliding with lighthouses (Mehlum 1977) and offshore oil industry installations (Lid 1977), as they become blinded or disorientated (e.g. Alerstam & Karlsson 1977). In the U.S.A., airport searchlights (ceilometers) in guy-wired steel towers cause the death of numerous birds (e.g. Arend 1970). The Electricity Supply Commission (ESCOM) in South Africa has tried to develop tubes suspended from the earth wire, utilizing the electric field around the conductors to produce low-intensity luminescent light (Longridge 1986).

(5) Acoustical scaring methods. Blokpoel (1976) reviewed the science of bioacoustics with regard to what is known to keep birds away from airports. Acoustical scaring devices do not seem to have been used to prevent collisions with power lines; however, wind-operated whistles or bells are attachable to overhead wires. As birds may be pests (e.g. to cereal and fruit farmers) and a danger to aircraft, numerous devices exist producing sounds that frighten birds (Boudreau

1968, Blokpoel 1976, Anonymous 1986). Distress and alarm calls of birds have been used for routine bird-scaring purposes. Blokpoel (1976) emphasized that further research might show that other calls could prove more effective.

Effect assessment of marking devices is difficult. As collisions with power lines frequently occur in bad weather and poor light, devices in categories 1–3 are of dubious value and mainly help diurnal species. However, marking has been claimed not only to increase wire visibility but also to help birds judge the distance to the wires, enabling them to make avoiding manoeuvres in time (Koops 1986). On the other hand, it has been pointed out that several marking devices of the spacer type, e.g. balloons, result in birds seeing the devices and adjusting their course between them but striking the wires nevertheless.

Koops (1986) stressed that there is evidence that collision frequency decreases when the space between wire-marking devices is short, e.g. 5 m. He argued that as most bird species have eyes placed on the side of the head, the viewing area observed straight ahead with both eyes at the same time, i.e. where the image will be stereoscopic and distance judgement will be possible, is relatively narrow. However, this conflicts with general knowledge about bird vision (Martin 1985, 1990, Schmidt-Morand 1992). The optical structure of the avian eye and the position and possibility for movement of the eye within the skull probably offer the majority of birds complete coverage of the visual world around as well as above them. Although not necessarily in a stereoscopic way, this gives birds excellent perception of the spatial relationships of structures and topographical features (Martin 1985, 1990).

Information on details of the vision of specific bird species will probably prove useful in attempts to develop efficient wire-marking devices. Because the foveal structure of the avian eye is thought to be of primary importance for position determination and movement detection (Pumphrey 1948), stationary marking devices can be expected to be less efficient than strip marking, which is a "moving" device. The first marking experiments on power lines apparently were made in 1964 in England (Scott *et al.* 1972). The 15-cm-long black strips used seemed to reduce collision frequency. However, later marking experiments using different strip varieties (ribbons, marker balls, etc.) hardly produced empirical support for an unambiguously positive effect, although observed mortality was reduced in several cases. Unfortunately, most studies have used methods which have not considered factors such as flight intensity, type of habitat, time of day/year as well as the great differences among bird species in their sensibility to light and response to weather conditions. Thus, possibilities for making reliable comparisons of pre- and post-marking collision rates are severely reduced.

An experiment in Colorado comparing collisions on power-line segments marked with either yellow spiral vibration dampers or swinging yellow fibreglass plates and unmarked segments showed a statistically significant reduction (>50%) in collisions for Sandhill Cranes *Grus canadensis*, Whooping Cranes *G. americana*, Canada Geese *Branta canadensis* and ducks (Brown & Drewien in press). Morkill & Anderson (in press) also observed a significant reduction in Sandhill Crane collisions in Nebraska when comparing unmarked segments and segments marked with yellow balls.

"Reaction studies" have been made, i.e. observations of how birds in flight react when they catch sight of an overhead wire ahead of them (e.g. Meyer 1978, James & Haak 1979, Willdan Associates 1982, Fredrickson 1983, Brown *et al.* 1987, Faanes 1987). This may be a useful technique for learning about the sensory effect of different marking devices on different species.

Wire marking has not proved to be the perfect solution, although the effectiveness of some marking methods that target specific species can hardly be questioned. However, it may still be claimed that marking justifies its cost mainly where spans are known to be dangerous to endangered and vulnerable species, although there is no broad agreement among biologists on this matter. It is claimed that the collision problem has more general relevance. Power lines obviously kill millions of birds each year, resident species as well as migrants during their migrations to and from their neo- and palaeotropical wintering grounds (e.g. Braaksma 1966, Renssen *et al.* 1975, N.-H. Gylstorff, unpubl. MSc thesis, University of Århus, Hoerschelmann *et al.* 1988). The general decrease observed in the numbers of several of these migratory species (cf. Lövei 1989) is a strong argument for research on bird interactions with utility structures.

From an engineering point of view, wire marking is not always a good solution. Devices which physically enlarge the wire commonly act as wind-catching objects, encouraging icing in winter and increasing the risk of wire and power breaks due to line tension and stress loads. The attachment of devices also may cause physical damage through abrasion to the conductors.

Neither optimal corridor location nor phase-conductor marking completely removes the collision problem. There is one reliable method left—underground cabling. The main argument against underground cables is their cost. It has been estimated (Madsen 1979) that underground cabling costs 10–30 times more than constructing 400-kV transmission lines, 4–7 times more than 132-kV lines and 3–4 times more than 50-kV lines. In general, above 15 kV costs rise exponentially (Thompson 1978, Longridge 1986).

Underground cabling has some technical disadvantages, e.g. fault searching and repairs are more complicated and expensive. At high tensions, cooling and capacitive currents also may cause problems (Madsen 1979). Where cables join an overhead power line, the transition from cable to air wire represents a weak point, especially when overstressed. These are major arguments for power companies when they are considering underground cabling for tensions above 20 kV. There are, however, technical advantages attached to underground cabling; the fault frequency throughout the year will be reduced and more evenly distributed in comparison with overhead wires.

Thus, underground cabling is not a general alternative for

Table 2. *Species reported as collision and/or electrocution victims and also included in "The ICBP World Check-list of Threatened Birds" (Collar & Andrew 1988)*

Species	Sources
Dalmatian Pelican *Pelecanus crispus*	Crivelli *et al.* (1988)
California Condor *Gymnogyps californianus*	Snyder (1986), Anonymous (1993)
Red Kite *Milvus milvus*	Haas (1980), Rose & Baillie (1992)
White-tailed Sea Eagle *Haliaëtus albicilla*	Bevanger & Thingstad (1988)
Cape Vulture *Gyps coprotheres*	Ledger & Annegarn (1981), Ledger (1984)
Black Vulture *Aegypius monachus*	Garzon (1977)
Imperial Eagle *Aquila heliaca adalberti*	Haas (1980), Meyburg (1989)
Manchurian Crane *Grus japonensis*	Brown *et al.* (1987)
Whooping Crane *Grus americana*	Brown *et al.* (1987)
Wattled Crane *Bugeranus carunculatus*	Johnson & Sinclair (1984), Ledger (1990)
Corncrake *Crex crex*	Bevanger & Thingstad (1988)

solving collision problems related to power lines. However, when new lines are being constructed, underground cabling must be considered as an alternative due to new production methods and decreased costs, at least for sections of the distribution system where problems with bird collisions have been recognized. All the low-tension distribution systems, both existing and planned, should be cabled underground.

THE ELECTROCUTION PROBLEM

Electrocution takes place whenever a bird touches two phase conductors or a conductor and an earthed device simultaneously (see Appendix for explanation of technical terms). This restricts the problem to power lines carrying tensions below about 130 kV and to transformer and substation installations. Electrocutions may seriously affect system reliability and may have major economic impacts. Hence, the electrocution problem was the first main aspect of interaction between birds and power supply on which research was carried out.

No one would question the need to have a stable energy supply in our society. Nearly all sectors are "computerized", and even with automatic reconnection, a "flash" caused by an electrocuted bird can be destructive to the industry. As many as 77% of Norwegian power companies have recognized birds as "energy-breakers" (Table 1).

The electrocution problem is somewhat easier to review than the collision problem, with respect to identifying the species involved in electrocution accidents, why they take place, and how to prevent accidents. However, the problem is complex because of the diversity of topographical aspects and diversity in electrical installations and equipment (e.g. Kroodsma & Van Dyke 1985)—as well as bird species—in different countries.

In common with collisions with power lines, electrocution has biological, topographical and technical aspects, although these are deeply interwoven and not easily separated. Weather conditions do not seem to have a serious influence, although humidity is important. Olendorff *et al.* (1981) referred to conductivity measurements on eagle feathers in the U.S.A., showing that current passes more easily through wet feathers than dry ones, making "low" voltages down to 5 kV dangerous.

Electrocution is not only a question of economy; several endangered and vulnerable bird species are known to be involved in these accidents, and attention should be paid to a wide variety of species so killed which are currently listed in the "*Red Data*" book (Table 2). Electrocution and the implementation of mitigating measures have mainly been studied in connection with raptors (Haas 1980, Olendorff *et al.* 1981, Williams & Colson 1989).

Biological aspects

The biological aspects are linked mainly to bird morphology and behavioural patterns. Body size is a key to understanding why birds are electrocuted. The relationship between wings, legs and body size and the "electrocuting traps", in principle, is simple.

Birds frequently find pylons or wires suitable as hunting posts and for resting, roosting (e.g. Young & Engel 1988) and nesting (e.g. Steenhof *et al.* 1988). Although the problems are associated primarily with the distribution system, nest building is a worldwide problem for reliable power-line operation, even at the highest tensions, since raptors and other species frequently use the towers as nesting sites. This, in part, is because they have lost their natural nesting habitats through the activities of man (e.g. deforestation) and because new habitats have been created by the tower constructions. Some power companies have modified the tower design to create nesting places for raptors and corvids or allowed nest boxes and nesting platforms to be built (e.g. Stahlecker 1979, Haas 1980, Olendorff *et al.* 1981).

The use of utility structures by birds is difficult to predict, as are the consequences of their activity. Excrement released by birds perched above certain installations may cause flashovers (Brown 1971, Engel in press). Prey or nesting material dropped onto phase conductors, etc., may result in phase–phase or phase–earth flashovers (Olendorff *et al.* 1981, Hobbs 1987). The nests on or near conductors in colonies of social weavers have been known to initiate bush fires. As the nests got damp, phase-to-phase arcing occurred and the nests caught fire. Electrocuted Cape Griffon *Gyps coprotheres* have caused fires in grassland in Transvaal (Hobbs & Ledger 1986, J. Ledger, pers. comm.). These types of bird activity may result in breaks in the electricity supply and/or the electrocution of a bird.

Topographical aspects

Power lines, poles and towers may be of benefit to raptors, owls and corvids where trees for nesting or roosting are rare, such as on the plains and in the deserts and intermontane basins of western North America (e.g. P.C. Benson, unpublished PhD thesis, Brigham Young University, Nelson 1982), and there are numerous reports of species using power-line pylons as nesting sites or hunting posts in flat landscapes (e.g. Olendorff *et al.* 1981, 1989, Brown & Lawson 1989). Power-line constructions in forested areas rarely are used for nesting. In Norway, except parts of the Finnmark area, few birds nest on pylons. Mass roosting on towers is also rare and has not been reported from Scandinavia.

The relationship between the electrocution hazard and the construction of electricity installations and habitat, behaviour and size of different bird species is illustrated by the Cape Griffons using 88-kV "kite" constructions as perches in the flat landscape of western Transvaal and other parts of South Africa. A study by Ledger (1984) revealed 246 electrocuted individuals of this vulnerable species (cf. Ledger 1990).

The route-planning process is also important in preventing electrocution accidents. The mapping of key areas is again fundamental. The neighbourhood of breeding habitats for raptors and owls, and the breeding sites of other species which commonly use wires or towers for perching and hunting posts, should be avoided.

Technical aspects

The major measures for preventing electrocution are the same as those recommended for dealing with the collision problem: removal of earth wires (and earthing modifications), line design modifications, route planning, underground cabling, tower design modifications and tower marking. Tower marking comprises visual and acoustical scaring methods of the types discussed earlier. The conclusions with regard to collision and underground cabling also apply to the electrocution problem.

Alternative technical solutions to earth wires are, in general, difficult to find. However, as regards the secondary distribution system where the earth wires are located either below or above the phase conductors, closer examination of the necessity of earthing should be undertaken. In Norway, earth wires on, for example, 20-kV lines are not installed primarily to drain overtensions caused by lightning but to secure proper earthing of the frequent pole-mounted transformers. These transformers should be earthed according to regulation standards, which means that the earth wire can be placed underground. In Norway, no standards state when earthing is necessary in relation to lightning frequency. Installation of earth wires is decided mainly on the basis of subjective assessment and partly because of "tradition" (E. Asbøll, pers. comm.).

If earth wires could be removed, the risk to birds with a large wing span of being electrocuted would be reduced. Large birds that perch on earth wires or conductors may touch these installations simultaneously when landing or taking off. A modification proposed by some authors (Miller *et al.* 1975, Olendorff *et al.* 1981) is to break the direct link between the steel cross-arm and the ground by making a spark gap in the earth wire. However, this conflicts with existing (Norwegian) regulations which state that all parts of a pole with conductive material must be directly earthed if entered by an earthed wire (e.g. a guy shroud) because of the danger to which personnel can be exposed during maintenance work.

Several authors have given special consideration to the design and configuration of poles, pylons and towers, cross-arms and conductors because of frequent electrocution of raptors and "unexplained" power outages (Haas 1980, Olendorff *et al.* 1981, Ledger 1984, Hobbs & Ledger 1986, Williams & Colson 1989). The main modifications proposed are elevated perch constructions, perching guards and lowering or extending cross-arms and pole tops to increase the critical distances between phase–phase or phase–ground, thus removing the "electrocuting trap" (Fig. 3) (see, e.g., Ansell & Smith 1980). The importance of focusing modification efforts on "preferred poles", i.e. particularly "lethal" poles, has been stressed (Olendorff *et al.* 1981, Williams & Colson 1989).

The questionnaire answers by Norwegian power companies revealed several types of electrical installations and equipment items associated with bird electrocution. As many as 73% of the answers confirmed that "bird electrocuting installations" had been identified. They can be classified in three main groups: (1) top-mounted pin insulators, (2) steel cross-arms and (3) pole-mounted transformers. Pole-mounted transformers are obviously the most dangerous electrocuting device in Norway (Fig. 4). A total of 127 (68%) power companies responding to the questionnaire (Table 1) mentioned pole-mounted transformers or equipment connected with them. These constructions cause electrocution because of the short distances between phase–phase and phase–ground. The same situation is experienced in South Africa (Ledger *et al.* in press).

In Sweden, a project was started to mitigate electrocution accidents on transformers (Lindgren 1984) due to the frequent electrocution of the Eagle Owl *Bubo bubo*, a species with vulnerable status in Scandinavia (Størkersen 1992). The project developed insulation methods for phase conductors and other conducting parts which could be achieved for a cost of £100–200 each. The problem will decrease in the future as new transformers are located on the ground, in closed buildings.

Hanging insulators prevent electrocution of birds perching on the cross-arm since there is no phase conductor above. The same effect is achieved if wood or another nonconductive material is used in the cross-arms. From a technical

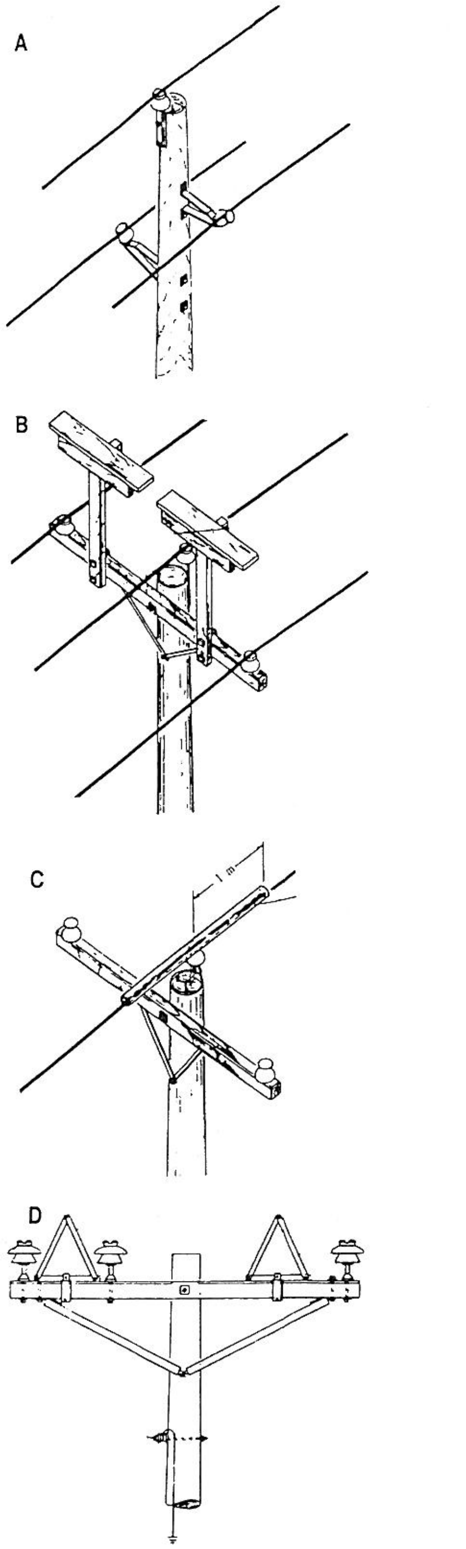

Figure 3. Examples of modifications to mitigate electrocution. (A) Armless configuration; (B) Elevated perch construction; (C) Conductor insulation alternative; (D) Perch guards. After Olendorff *et al.* (1981).

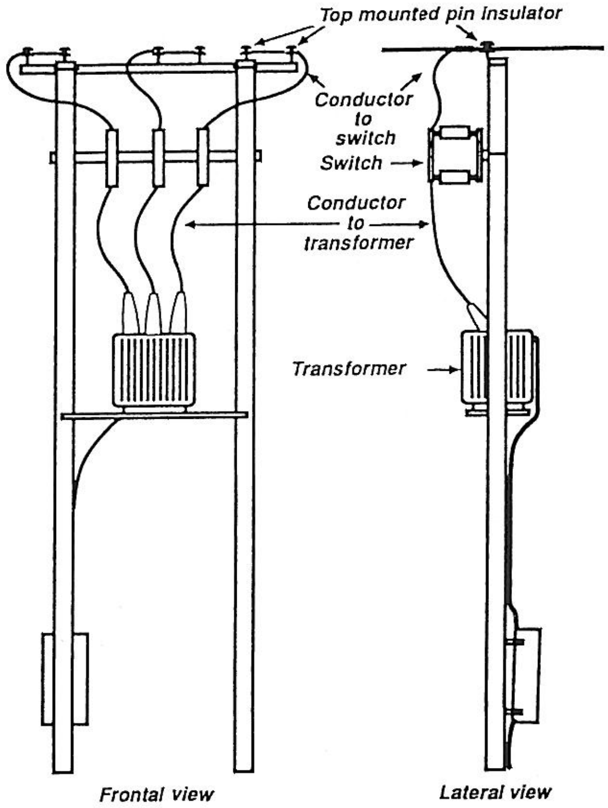

Figure 4. Sketch of a pole-mounted transformer construction. The combination of a design offering broad perching opportunities and short distances between the electrified wires and between the electrified wires and earthed materials makes this construction an "electrocuting trap", particularly dangerous to perching birds, e.g. raptors and owls.

point of view, however, this might cause problems where the need for earthing is high. An alternative is to coat the cross-arms with insulation. Experiments with this have been performed in Germany (cross-arms with "Schutzanstrich") with positive results (Haas 1975). For cross-arms on especially exposed pylons, an alternative is to coat a short section of the phase conductors with an insulating plastic. A special "bird protector" may be mounted on spark gaps (see Bevanger & Thingstad 1988). The German power companies have jointly published a booklet on various design and technical alternatives for constructing pylons, cross-arms and configurations (VDEW 1986).

CONCLUSIONS

It has been difficult for the topic of the interactions of birds with utility structures to leave the "report" and descriptive stages. Analytical and deductive methods in the majority of "collision" projects, and experimental data, are rare, and the premises for some investigations obviously have not been set by biologists.

It is thoroughly documented that substantial losses occur by birds flying into power lines and by electrocution accidents. Assessing the numbers of casualties and the characteristics of the accident hot spots has so far been the main concern. A broad range of basic biological research requirements in vision, biomechanics and flight behaviour, migration patterns and population dynamics have been merely touched upon. Combined with information about effects of geographical characteristics (meteorology, topography, light conditions, etc.), new information about these biological aspects offers a tool for predicting potential collision hazards to different species and should be introduced as an important aspect of this work.

Efficient mitigating measures are difficult to develop in the absence of this information. Measures should be directed against the target species, i.e. those shown to be the potential victims. Birds with a wide variety of morphological and ecological adaptations have been identified among the casualties. The colour and shape of wire-marking devices must be researched as well as numerous physiological questions related to auditive and visual characteristics of different bird species.

There are an alarming number of species with endangered or vulnerable status involved in these accidents. Thus, efforts to reduce this mortality have a conservational value. The "power-line load" an area can endure before significant population damage occurs to bird species needs to be known, and more sophisticated risk analysis techniques should be used (cf. Akcakaya in press) to predict the effects of these mortality factors at the population level.

The electrocution problem has been investigated thoroughly, probably because of its serious economic impact. More than 55% of Norwegian power companies regarded birds as a problem in their supply district (Table 1). Electrocution hazards have become predictable, with regard to both the type of electrical equipment involved and the bird species that are most vulnerable. Although engineers, in cooperation with biologists, already have performed well in modifying electrical equipment to avoid electrocuting birds, there are still challenging "technical" questions connected with both transformer and tower designs. As many as 64% of the Norwegian power companies admitted to not having made technical improvements despite recognizing that there were many "bird electrocuting installations" in their supply district (Table 1). A comprehensive compilation of existing solutions in a booklet which could be distributed worldwide should be made. Several power companies still are ignorant about the research that has been done.

New power lines are inevitably going to appear in the years to come. There are still huge areas in Africa, South America and Asia where the majority of people live without electricity. The developing countries will probably have thousands of kilometres of new power lines built during the coming decades. Although birds have not been a main topic of concern for economic donors and technical aid to Third World countries so far, the use of bird-friendly structures depends on how professionals and conservationists manage to raise general awareness of the problem. Indeed, power companies worldwide should be encouraged to use bird-friendly designs for their utility structures and be properly advised on route planning to avoid key functional areas for birds.

I am indebted to Richard Binns for improving the English, to Anja Lydersen for patiently translating Dutch papers into Norwegian and especially to several colleagues at the Norwegian Institute for Nature Research and John Ledger for valuable comments on the manuscript.

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Submitted 28 April 1993; revision accepted 27 September 1993

APPENDIX

Explanatory notes to frequently used technical terms

capacitive current: electricity displaced 90° in front of the main current

conductor (or phase conductor): an electrified wire. Transmission lines frequently have duplex, triplex or quadriplex configuration, i.e. the phase consists of two, three or four conductors in a bundle

cross-arm: horizontal mounted bar of steel or wood in poles and pylons carrying the insulators (and wires)

earth wire (top wire, ground wire, neutral conductor): a wire usually located above, but also below, the conductors to intercept and drain overtensions (usually created by lightning discharges but also because of insulation contamination, moisture, etc.)

electrocution: killing by electricity—occurs when a body simultaneously touches two electrified wires or one electrified wire and an earthed device (or earth wire)

flashover: occurs when the distance between two conductors or one conductor and an earthed device becomes narrow enough for an arc to jump, causing a short circuit

insulator: device of nonconductive material for suspending the phase conductors or earth wires; pin insulators are mounted at the upper side of the cross-arm, hanging insulators below the cross-arm

spark gap: construction to reduce the isolating durability to preferred level in the case of overtensions

transformer: a device for converting the current from one voltage level to another